IEEE Std C57.12.91-2001
(Revision of
IEEE Std C57.12.91-1995)

IEEE Standard Test Code for Dry-Type Distribution and Power Transformers

Sponsor

Transformers Committee
of the
IEEE Power Engineering Society

Approved 9 January 2001

IEEE-SA Standards Board

Abstract: Methods for performing tests specified in IEEE Std C57.12.01-1998 and other referenced standards applicable to dry-type distribution and power transformers are described. This standard is intended for use as a basis for performance, safety, and the proper testing of dry-type distribution and power transformers. This standard applies to all dry-type transformers except instrument transformers, step-voltage and induction voltage regulators, arc furnace transformers, rectifier transformers, specialty transformers, and mine transformers.
Keywords: dry-type transformer, power transformer

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Introduction

(This introduction is not a part of IEEE Std C57.12.91-2001, IEEE Standard Test Code for Dry-Type Distribution and Power Transformers.)

This revision of IEEE Std C57.12.91-1995 changes Clause 9 only to include the associated leads or bus bar during the measurement of load loss and the measurement of impedance voltage.

The working group, as promised after publication of the 1995 revision, reviewed Subclause10.8 on insulation power-factor tests. It is the consensus of the working group that the clause should not be changed from the 1979 revision.

Hottest-spot temperature rise is a performance parameter to be met by the manufacturer to conform to IEEE Std C57.12.01-1998. It is not economically practical to measure hottest-spot temperature rise on the primary and secondary windings of all dry-type transformers. Conformance to average temperature rise limits in IEEE Std C57.12.01-1998 does not automatically assure that hottest-spot temperature rise limits are met, due to the wide range of sizes of transformers covered by IEEE Std C57.12.01-1998. A reduction of average winding temperature rise below the limits may be required to meet hottest-spot temperature rise limits. Since the publication of IEEE Std C57.12.91-1995, IEEE Std C57.134-2000, IEEE Guide for Determination of Hottest Spot Temperature in Dry Type Transformers has been developed. This guide describes methodologies for determining the steady state winding hottest spot temperature in dry-type distribution and power transformers.

This standard is a voluntary consensus standard. Its use may become mandatory only when required by a duly constituted legal authority, or when specified in a contractual relationship. To meet specialized needs and to allow innovation, specific changes are permissible when mutually determined by the user and the producer, provided such changes do no violate existing laws, and are considered technically adequate for the function intended.

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The final conditions for approval of this standard were met on 9 January 2001. This standard was conditionally approved by the IEEE-SA Standards Board on 7 December 2000, with the following membership:

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Contents

IEEE Standard Test Code for Dry-Type Distribution and Power Transformers

1. Scope

This standard describes methods for performing tests specified in IEEE Std C57.12.01-1998[1] and other referenced standards applicable to dry-type distribution and power transformers. It is intended for use as a basis for performance, safety, and the proper testing of dry-type distribution and power transformers.

This standard applies to all dry-type transformers except instrument transformers, step-voltage and induction voltage regulators, arc furnace transformers, rectifier transformers, specialty transformers, and mine transformers.

1.1 Purpose

The purpose of this standard is to provide test procedure information. Transformer requirements and specific test criteria are not a part of this standard but are contained in appropriate standards such as IEEE Std C57.12.01-1998 or in user specifications.

1.2 Word usage

When this standard is used on a mandatory basis, the word *shall* indicates mandatory requirements; the words *should* or *may* refer to matters that are recommended or permissive, but not mandatory.

NOTE—The introduction of this standard describes the circumstances in which the standard may be used on a mandatory basis.

2. References

Various standards and guides are listed below. References are identified throughout this standard by designation number and year.

When the standards referenced in this standard are superseded by a revision, the latest revision shall apply.

[1]Information on references can be found in Clause 2.

ANSI C57.12.50-1981 (Reaff 1998), American National Standard Requirements for Ventilated Dry-Type Distribution Transformers 1 to 500 kVA, Single-Phase; and 15 to 500 kVA, Three-Phase with High-Voltage 601 to 34 500 Volts, Low Voltage 120 to 600 Volts.[2]

ANSI C57.12.51-1981 (Reaff 1998), American National Standard Requirements for Ventilated Dry-Type Power Transformers 501 kVA and Larger, Three-Phase, with High-Voltage 601 to 34 500 Volts, Low-Voltage 208Y/120 to 4160 Volts.

ANSI C57.12.52-1981 (Reaff 1998), American National Standard Requirements for Sealed Dry-Type Power Transformers 501 kVA and Larger, Three-Phase with High-Voltage 601 to 34 500 Volts, Low-Voltage 208Y/120 to 4160 Volts.

ANSI C57.12.55-1987 (Reaff 1998), American National Standard for Dry-Type Transformers Used in Unit Installations, Including Unit Substations—Conformance Standard.

ANSI C57.12.57-1987, American National Standard Requirements for Ventilated Dry-Type Network Transformers 2500 kVA and Below, Three-Phase, High-Voltage 34 500 Volts and Below, Low-Voltage 216Y/125 and 480Y/277 Volts.

ANSI S1.4-1983, American National Standard Specification for Sound Level Meters.

ANSI S1.11-1986 (Reaff 1998), American National Standard Specifications for Octave-Band and Fractional Octave-Band Analog and Digital Filters.

IEEE Std 4-1995, IEEE Standard Techniques for High-Voltage Testing.[3]

IEEE Std 99-1980 (Reaff 2000), IEEE Standard for the Preparation of Test Procedures for the Thermal Evaluation of Solid Electrical Insulating Materials.

IEEE Std C57.12.01-1998, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid Cast and/or Resin-Encapsulated Windings.

IEEE Std C57.12.56-1986 (Reaff 1998), IEEE Standard Test Procedure for Thermal Evaluation of Insulation Systems for Ventilated Dry-Type Power and Distribution Transformers.

IEEE Std C57.12.58-1991 (Reaff 1996), IEEE Guide for Conducting a Transient Voltage Analysis of a Dry-Type Transformer Coil.

IEEE Std C57.12.59-1989, IEEE Guide for Dry-Type Transformer Through-Fault Current Duration.[4]

IEEE Std C57.12.60-1998, IEEE Guide for Test Procedures for Thermal Evaluation of Insulation Systems for Solid-Cast and Resin-Encapsulated Power and Distribution Transformers.

IEEE Std C57.12.70-2001, IEEE Standard Terminal Markings and Connections for Distribution and Power Transformers.

[2]ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA (http://www.ansi.org/).

[3]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).

[4]IEEE Std C57.12.59-1989 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181 (http://global.ihs.com/).

IEEE Std C57.12.80-1978 (Reaff 1992), IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.96-1999, IEEE Guide for Loading Dry-Type Distribution and Power Transformers.

IEEE Std C57.98-1993 (Reaff 1999), IEEE Guide for Transformer Impulse Tests.

IEEE Std C57.124-1991, IEEE Recommended Practice for the Detection of Partial Discharge and the Measurement of Apparent Charge in Dry-Type Transformers.

IEEE Std C57.134-2000, IEEE Guide for Determination of Hottest Spot Temperature in Dry Type Transformers.

3. Definitions

Standard transformer terminology available in IEEE Std C57.12.80-1978 shall apply. Other electrical terms are defined in *The Authoritative Dictionary of IEEE Standards Terms,* Seventh Edition.

4. General

4.1 Test definitions

Various types of tests such as *routine*, *design*, *other*, and *conformance* are defined in IEEE Std C57.12.80-1978.

4.2 Test requirements

A general summary of test requirements is included in Table 15 of IEEE Std C57.12.01-1998, which indicates by size (500 kVA and smaller, or 501 kVA and larger) which tests are normally considered *routine*, *design*, or *other*.

4.3 Test sequence

See 10.1.5.4 for sequence of dielectric tests when lightning impulse tests are specified.

NOTE—If it is desired to minimize potential damage to the transformer during testing, the resistance, polarity, phase-relation, ratio, no-load-loss and excitation current, impedance and load-loss tests, and temperature-rise tests (when applicable) should precede dielectric tests. When this sequence is used, the beginning tests involve voltages and currents that are usually reduced compared to rated values, thus tending to minimize damaging effects to the transformer.

4.4 Instrumentation

Although the figures in this standard show conventional meters, adequate digital-readout measuring devices and digital sampling techniques with computer calculations are considered satisfactory alternatives.

5. Resistance measurements

5.1 General

Resistance measurements are of fundamental importance for the calculation of the I^2R component of conductor losses, for the calculation of winding temperatures at the end of a temperature rise test, and as a base for assessing possible damage in the field.

Cold-resistance measurements shall be taken on all phases of each primary and secondary winding on the rated tap connection. If a temperature rise test is to be performed, cold resistance measurements shall also be taken on all phases of each primary and secondary winding on the combination of connections and taps to be used for the temperature rise test. When transferring leads from one winding to another, the same relative polarity should be maintained with regard to the measuring leads and the transformer terminals.

The induction time for the measuring current to become stable should be noted during the cold-resistance measurements in order to ensure that sufficient time elapses for the induction effect to disappear before hot resistance readings are taken during the temperature rise tests. Cold-resistance measurements shall not be made on a transformer when it is located in drafts or when it is located in a room in which the temperature is fluctuating rapidly.

5.2 Determination of cold temperature

The cold temperature of the winding shall be determined as accurately as possible when measuring the cold resistance. The following precautions shall be observed. The temperature of the windings for ventilated units shall be recorded as the average readings of several thermometers or thermocouples inserted between the coils. Care shall be taken to see that the measuring points of the thermocouples or thermometers are as nearly as possible in actual contact with the winding conductors. The temperature of the windings for sealed units shall be recorded as the average readings of several temperature sensors in contact with the tank and cover (see 11.8.6 and Figure 30).

It should not be assumed that the windings are at the same temperature as the surrounding air. To ensure that the windings are at ambient temperature, the following conditions shall be met immediately before taking cold-resistance measurements:

a) All internal temperatures measured by the internal temperature sensors shall not differ from ambient temperature by more than 2 °C.
b) Tank surface temperatures for sealed units shall not differ from ambient temperature by more than 2 °C.
c) Ambient temperature shall not have changed by more than 3 °C for at least 3 h.
d) The transformer has been in a draft-free area for 24 h and neither voltage nor current has been applied to it for 24–72 h, depending on its size.

5.3 Conversion of resistance measurements

Cold-winding resistance measurements are normally converted to a standard reference temperature equal to rated average winding temperature rise plus 20 °C. In addition, it may be necessary to convert the resistance measurements to the temperature at which the impedance-loss measurements were made. The conversions are accomplished by the following formula:

$$R_s = R_m[(T_s + T_k)/(T_m + T_k)] \tag{1}$$

where

R_s is resistance at desired temperature, T_s,
R_m is measured resistance,
T_s is desired reference temperature,
T_k is 234.5 for copper, 225 for aluminum,
T_m is the temperature at which resistance was measured.

NOTE—The value of T_k may be as high as 240 °C for alloyed aluminum.

5.4 Resistance measurement methods

5.4.1 Bridge method

Bridge methods (or high-accuracy digital instrumentation) are generally preferred because of their accuracy and convenience since they may be employed for the measurement of resistances up to 10 000 Ω. They should be used in cases where the rated current of the transformer winding to be measured is less than 1 A.

NOTE—For resistance values of 1 Ω or more, a Wheatstone bridge (or equivalent) is commonly used; for values less than 1 Ω, a Kelvin bridge (or equivalent) is commonly used. Some modern resistance bridges have capability in both ranges.

5.4.2 Voltmeter-ammeter method

The voltmeter-ammeter method is sometimes more convenient than the bridge method. It should be employed only if the rated current of the transformer winding is 1 A or more. Digital voltmeters and digital ammeters of appropriate accuracy are commonly used in connection with temperature-rise determinations.

5.4.2.1 The measuring circuit

Measurement is made with direct current, and simultaneous readings of current and voltage are taken using the connections of Figure 1. The required resistance is calculated from the readings in accordance with Ohm's law. A battery or filtered rectifier will generally be found to be more satisfactory as a dc source than will a commutating machine. The latter may cause the voltmeter pointer to vibrate because of voltage ripple.

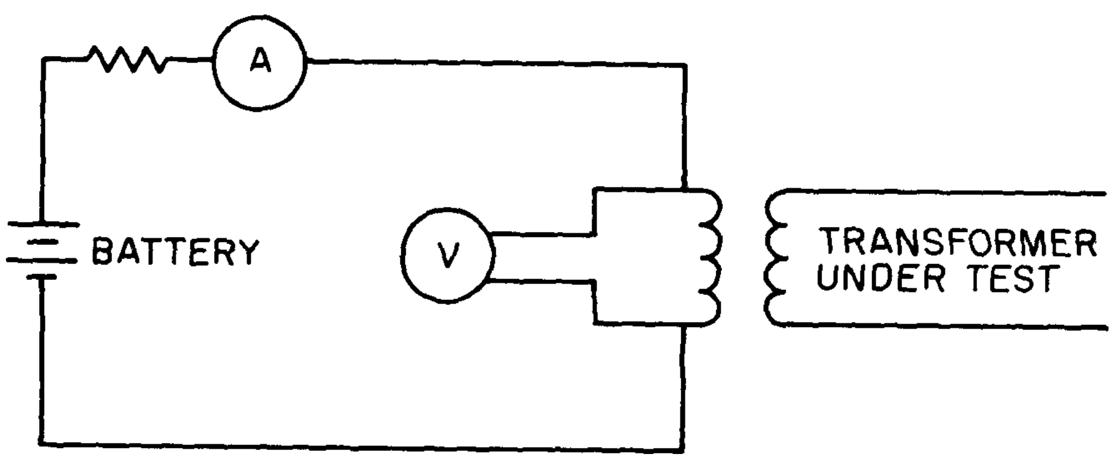


Figure 1—Connections for the voltmeter-ammeter method of resistance measurement

5.4.2.2 Minimizing errors

In order to minimize errors of observation, the following shall be implemented:

a) The range of analog measuring instruments shall be such as to give a reasonably large deflection.
b) The polarity of the core magnetization shall be kept constant during all resistance readings.

NOTE—A reversal in magnetization of the core can change the time constant and result in erroneous readings.

5.4.2.3 Independent voltmeter and current leads

The voltmeter leads shall be independent of the current leads and shall be connected as closely as possible to the terminals of the winding to be measured. This is to avoid including in the reading the resistances of current-carrying leads and their contacts and of extra lengths of leads. To protect the voltmeter from injury by off-scale deflections, the voltmeter should be disconnected from the circuit before the current is switched on or off. To protect test personnel from *inductive kick*, the current should be switched off by a suitably insulated switch.

If the drop of voltage is less than 1 V, a potentiometer or millivoltmeter shall be used.

5.4.2.4 The effect of winding dc time constant

Readings shall not be taken until after the current and voltage have reached steady-state values.

When measuring the cold-resistance preparatory to making a heat run, the time required for the readings to become constant should be noted. The period thereby determined should be allowed to elapse before taking the first reading when final winding hot-resistance measurements are being made.

In general, the winding will exhibit a long dc time constant. To reduce the time required for the current to reach its steady-state value, a noninductive external resistor should be added in series with the dc source. The resistance should be large compared to the inductance of the winding. It will then be necessary to increase the source voltage to compensate for the voltage drop in the series resistor. The time will also be reduced by operating all other transformer windings open-circuited during the tests.

5.4.2.5 Maximum dc current in measuring circuit

Readings shall be taken with not less than four values of current when deflecting instruments are used. The average of the resistances calculated from these measurements shall be considered to be the resistance of the circuit.

The current used shall not exceed 15% of the rated current of the winding's resistance to be measured. Larger values may cause inaccuracy by heating the winding and thereby changing its temperature and resistance.

When the current is too low to be read on a deflecting ammeter, a shunt and digital millivoltmeter or potentiometer shall be used.

6. Polarity and phase-relation tests

Polarity and phase-relation tests are of interest primarily because of their bearing on paralleling or banking two or more transformers. Phase-relation tests are made to determine angular displacement and relative phase sequence.

6.1 Subtractive and additive polarity

Windings arranged for subtractive and additive polarity are shown in Figure 2 and Figure 3. Leads and polarity marks arranged for subtractive polarity and additive polarity are shown in Figure 4 and Figure 5.

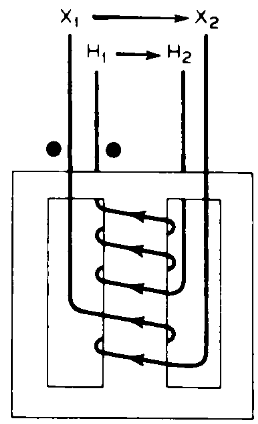


Figure 2—Windings: subtractive polarity

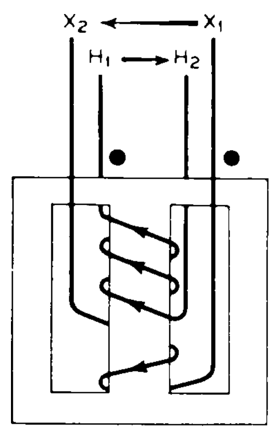


Figure 3—Windings: additive polarity

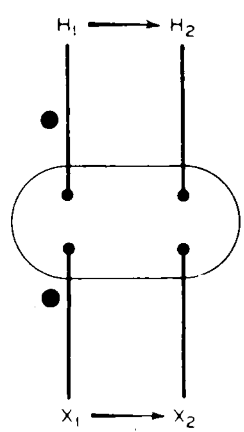


Figure 4—Leads and polarity marks: subtractive polarity

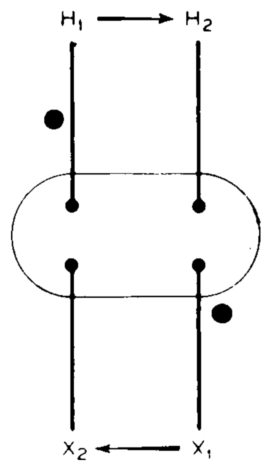


Figure 5—Leads and polarity marks: additive polarity

6.2 Polarity tests—single-phase transformers

Polarity tests on single-phase transformers are commonly made in accordance with one of the following methods:

a) Inductive kick
b) Alternating voltage
c) Comparison
d) Ratio bridge

6.2.1 Polarity by inductive kick

The polarity of transformers with leads arranged as shown in Figure 2, Figure 3, Figure 4, and Figure 5 may be determined at the time of making the resistance measurements as follows:

a) With direct current passing through the high-voltage winding, connect a high-voltage dc voltmeter across the high-voltage winding terminals so as to get a small deflection of the pointer.
b) Transfer the two voltmeter leads directly across the transformer to the adjacent low-voltage leads, respectively.
c) Break dc excitation, thereby inducing a voltage in the low-voltage winding (inductive kick) that will cause a deflection in the voltmeter, which is interpreted in item d) and item e).
d) If the pointer swings in the opposite direction (negative), the polarity is subtractive.
e) If the pointer swings in the same direction as before (positive), the polarity is additive.

NOTE—For example, in Figure 5, the voltmeter lead connected to H_1 will be transferred to X_2 as the adjacent lead, and the voltmeter lead connected to H_2 to X_1.

6.2.2 Polarity by alternating-voltage test

For transformers having a ratio of transformation of 30 to 1 or less, the H_1 lead shall be connected to the adjacent low-voltage lead. (In Figure 6, this will be X_1.)

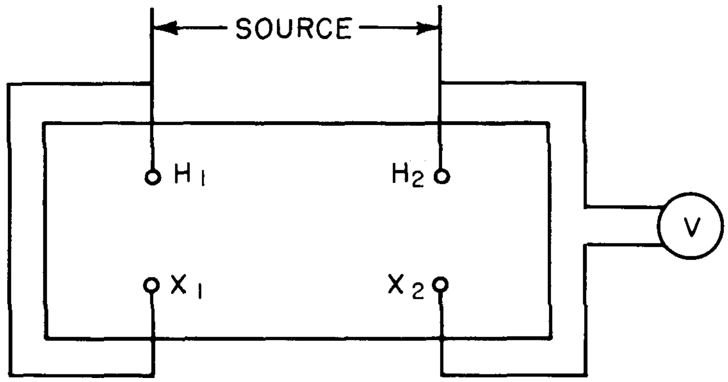


Figure 6—Polarity by alternative-voltage test

Any convenient value of alternating voltage shall be applied to the full high-voltage winding and readings taken of the applied voltage and the voltage between the right-hand adjacent high-voltage and low-voltage leads. If the latter reading is greater than the former, the polarity is additive. If the latter voltage reading is less than the former (indicating the approximate difference in voltage between that of the high-voltage and low-voltage windings), the polarity is subtractive.

6.2.3 Polarity by comparison

When a transformer of known polarity and of the same ratio as the unit under test is available, the polarity can be checked by comparison, as follows, similar to the comparison method used for the ratio test (see Figure 9 and Figure 10):

a) Connect the high-voltage windings of both transformers in parallel by connecting similarly marked leads together.
b) Also connect the low-voltage leads, X_2, of both transformers together, leaving the X_1 leads free.
c) With these connections, apply a reduced value of voltage to the high-voltage windings and measure the voltage between the two free leads. A zero or negligible reading of the voltmeter will indicate that the relative polarities of both transformers are identical.
d) An alternative method of checking the polarity is to substitute a low-rated fuse or suitable lamps for the voltmeter. This procedure is recommended as a precautionary measure before connecting the voltmeter.

6.2.4 Polarity by ratio bridge

The ratio bridge described in Clause 7 can also be used to test polarity.

6.3 Polarity and phase-relation tests—polyphase transformers

6.3.1 Polarity

Each phase of a polyphase transformer shall have the same relative polarity when tested in accordance with one of the methods described for single-phase transformers.

6.3.2 Phase-relation tests

6.3.2.1 Test to verify phasor diagram for transformers with a ratio of transformation of 60 to 1 or less

The phasor diagram of any three-phase transformer, defining both the angular displacement and phase sequence, can be verified by connecting the H_1 and X_1 leads together; exciting the unit at a suitably low, three-phase voltage; taking voltage measurements between various pairs of leads; and then either plotting these values or comparing them for their relative order of magnitude with the help of the corresponding diagram in Figure 7 or Figure 8, in which typical check measurements to be taken and their relative magnitudes are also indicated.

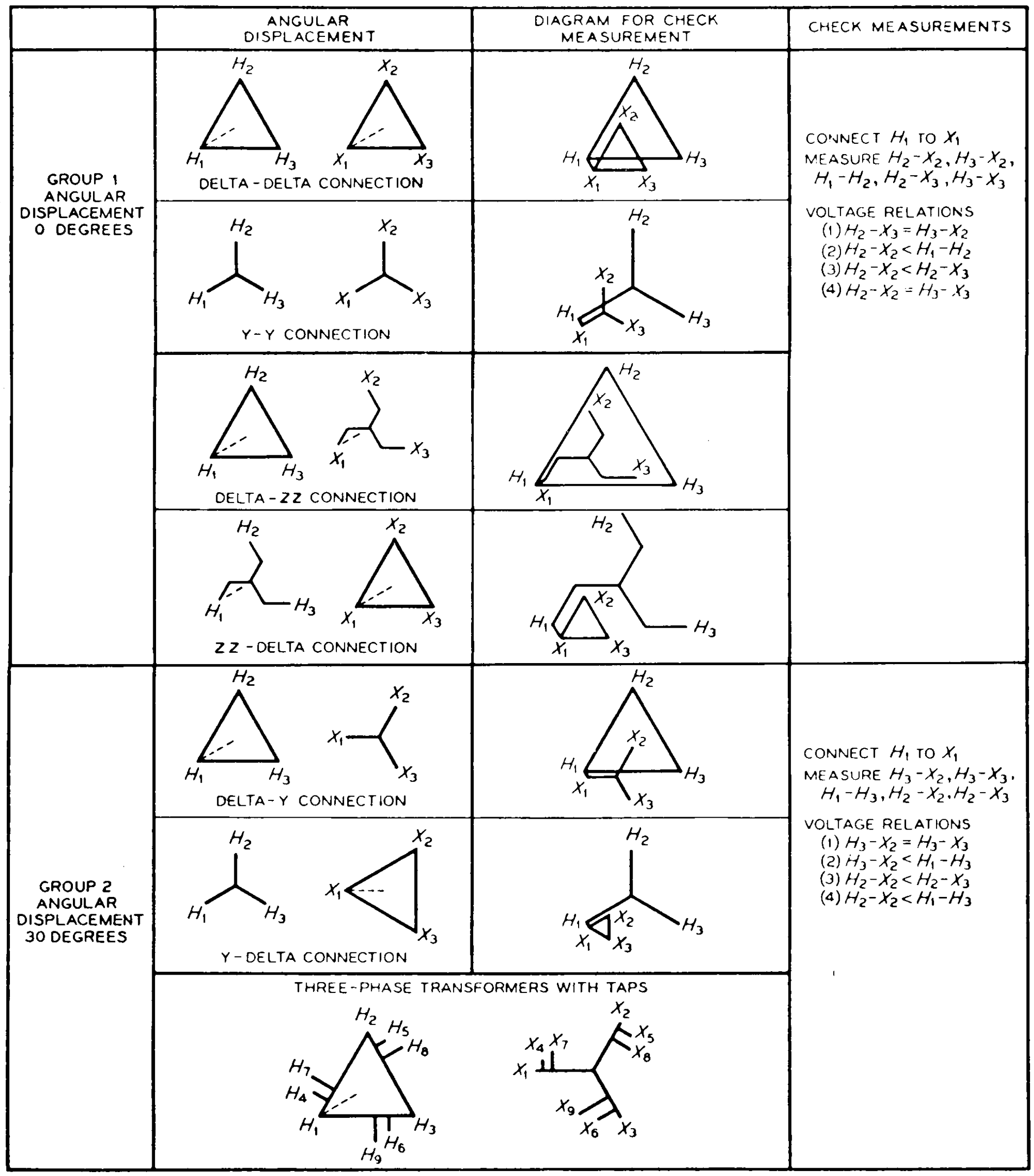


Figure 7—Transformer lead markings and voltage-phasor diagrams for three-phase transformer connections

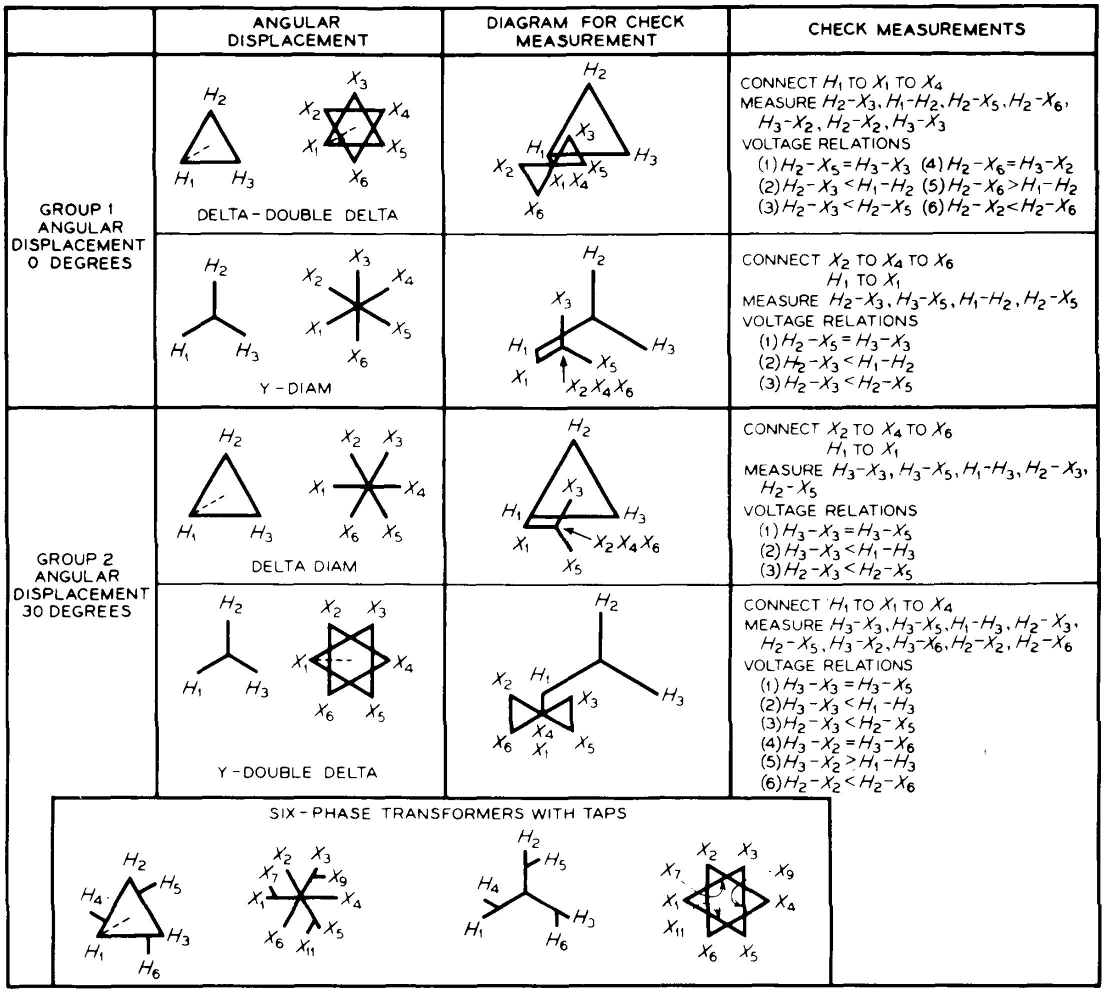


Figure 8—Transformer lead markings and voltage-phasor diagrams for six-phase transformer connections

6.3.2.2 Zigzag windings

Equal zig and zag windings usually are necessary for zigzag transformers, although unequal windings may be used for special applications.

No required test is proposed to determine the phase relationships between the line-end and neutral-end sections of a zigzag winding. However, it is recommended that a test connection be made to the junction of the two-winding sections, and that tests be made during the manufacturing phase to prove the desired phase relationships. For the purpose of designation in Figure 7, zigzag windings are arbitrarily defined as windings whose line-end section is rotated 60 degrees counterclockwise with respect to the neutral-end section.

6.3.2.3 Six-phase windings

Six-phase windings with no neutral connection shall be temporarily connected in delta or wye for the test for phasor diagram.

6.3.2.4 Phase relation with ratio bridge

The ratio bridge described in 7.3.3 can also be used to test phase relationships.

6.3.3 Phase-sequence test

The following method does not disclose the angular displacement of the transformer. The phase-sequence indicator may incorporate either a three-phase induction motor or a split-phase circuit.

It should be connected first to the higher voltage leads; the transformer should be excited three-phase at a low voltage suitable for the indicator, and the direction of rotation of the indication of the instrument should be noted.

The indicator is then transferred to the low-voltage side of the transformer, connecting to X_1 the lead that was connected to H_1, connecting to X_2 the lead that was connected to H_2, and connecting to X_3 the lead that was connected to H_3.

The transformer is again excited at a suitable voltage (without changing the excitation connections) and the indication again noted. The phase sequence of the transformer is correct if the indication is the same in both cases.

Six-phase secondaries, having no neutral connection, have to be connected temporarily in delta or wye for this test also. If a six-phase neutral is available, the phase-sequence indicator leads should be transferred from H_1 to X_1, from H_2 to X_3, and from H_3 to X_5, respectively, and the direction of rotation noted. The tests should then be repeated by transferring from H_1 to X_2, from H_2 to X_4, and from H_3 to X_6, respectively, and noting the indication, which should be the same as before.

6.3.3.1 Test of phase-sequence with ratio bridge

The ratio bridge described in Clause 7 can also be used to test phase sequence.

7. Ratio tests

7.1 General

The turns ratio of a transformer is the ratio of the number of turns in a higher voltage winding to that in a lower voltage winding.

7.1.1 Transformers with taps

When a transformer has taps for changing its voltage ratio, the turns ratio is based on the number of turns corresponding to the normal rated voltage of the respective windings to which operating and performance characteristics are referred.

When the transformer has taps, the turns ratio shall be determined for all taps, as well as for the full winding.

7.1.2 Voltage and frequency requirements

The ratio test shall be made at rated or lower voltage and rated or higher frequency.

7.1.3 Three-phase transformers

In the case of three-phase transformers, when each phase is independent and accessible, single-phase power should preferably be used, although when convenient, three-phase power may be used.

7.1.4 Transformers with wye-diametric connections

Transformers that have wye-diametric connections but do not have the neutral of the wye brought out may be tested for ratio with three-phase power. Any inequality in the magnetizing characteristics of the three phases will then result in a shift of the neutral, thereby causing unequal diametric voltages. When such inequality is found, the diametric connection should be changed to either delta- or wye-connection and the line voltages should be measured. When these are found to be equal to each other and of proper value (1.73 times the diametric voltages if connected in wye), the ratio is correct.

7.1.5 Inaccessible neutrals

An alternative test procedure, using single-phase power, is possible resulting in negligible loss of accuracy. When only one winding has an inaccessible neutral, a connection to that neutral can be made through a coil on another phase leg. This is accomplished by shorting the energized winding on that phase leg, thereby reducing the flux in that leg to zero. With zero flux there is no voltage induced in the coil being used for the connection, and the only error is due to the added resistance of that coil. When neutrals are inaccessible on both the primary and secondary windings, the ratio can be determined using single-phase power connected line-to-line.

7.2 Tolerances for ratio

See Clause 9 of IEEE Std C57.12.01-1998.

7.3 Ratio test methods

7.3.1 Voltmeter method

Two voltmeters shall be used (with voltage transformers if necessary)—one to read the voltage of the high-voltage winding, and the other to read that of the low-voltage winding. The two voltmeters shall be read simultaneously.

A second set of readings shall be taken with the instruments interchanged, and the average of the two sets of readings shall be taken to compensate for instrument errors.

Voltage transformer ratios should be such as to yield about the same readings on the two voltmeters, otherwise compensation for instrument errors by an interchange of instruments will not be satisfactory, and it will be necessary to apply appropriate corrections to the voltmeter readings.

Tests shall be made at not less than four voltages in approximately 10% steps, and the average result shall be taken as the true value. These several values should check within 1% of each other. Otherwise, the tests shall be repeated with other voltmeters.

When appropriate corrections are applied to the voltmeter readings, tests may be made at only one voltage.

When several transformers of duplicate rating are to be tested, work may be expedited by applying the foregoing tests to only one unit and then comparing the other units with this one as a standard in accordance with the comparison transformer method discussed in 7.3.2.

7.3.2 Comparison method

A convenient method of measuring the ratio of a transformer is by comparison with a transformer of known ratio.

The transformer to be tested is excited in parallel with a transformer of the same nominal ratio, and the two secondaries are connected in parallel but with a voltmeter or detector in the connection between two terminals of similar polarity (see Figure 9). This is the more accurate method because the voltmeter or detector indicates the difference in voltage.

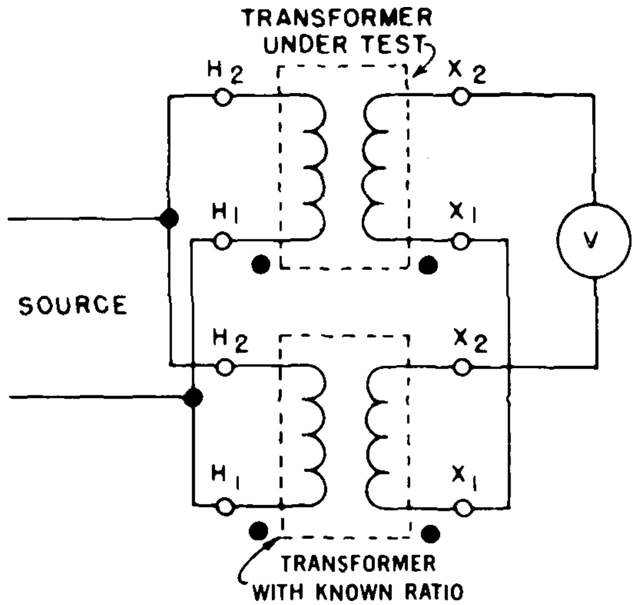


Figure 9—Voltmeter arranged to read the difference between the two secondary voltages

For an alternate method, the transformer to be tested is excited in parallel with a transformer of known ratio, and the voltmeters are arranged to measure the two secondary voltages (see Figure 10).

The voltmeters shall be interchanged and the test shall be repeated. The averages of the results are the correct voltages.

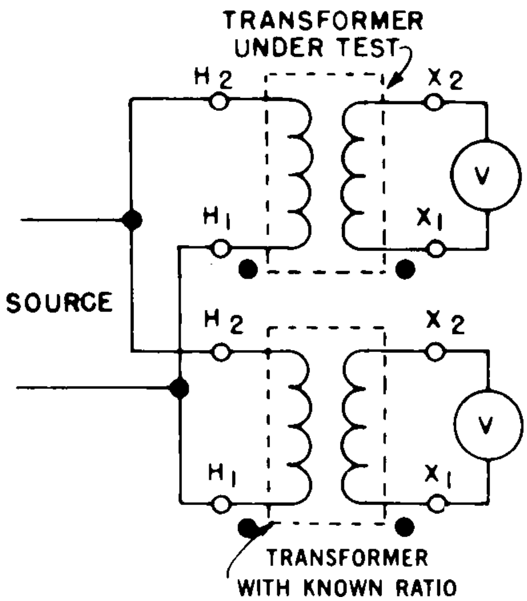


Figure 10—Voltmeters arranged to read the two secondary voltages

7.3.3 Ratio bridge

A bridge using the basic circuit of Figure 11 may be used to measure ratio. When detector (DET) is in balance, the transformer ratio equals R/R_1.

NOTES:

1—Measurement of the ratio using circuits of this type has also (in the past) been described as *ratio by resistance potentiometer.*

2—More accurate results can be obtained using a ratio bridge that provides phase-angle correction.

3—The ratio bridge can also be used to test polarity, phase relation, and phase sequence.

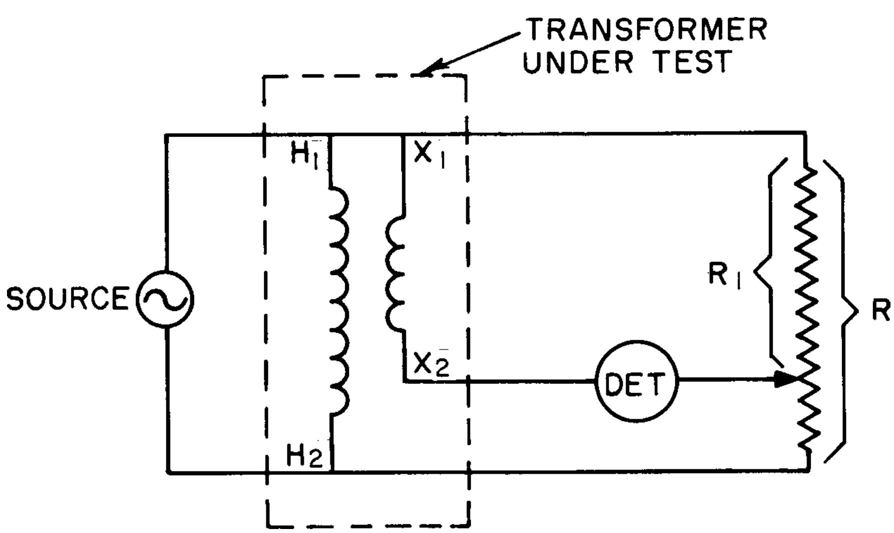


Figure 11—Basic circuit of ratio bridge

8. No-load losses and excitation current

8.1 General

No-load (excitation) losses are those losses that are incident to the excitation of the transformer. No-load (excitation) losses include core loss, dielectric loss, conductor loss in the winding due to excitation current, and conductor loss due to circulating current in parallel windings. These losses change with the excitation voltage.

Excitation current (no-load current) is the current that flows in any winding used to excite the transformer when all other windings are open-circuited. It is generally expressed in percent of the rated current of the winding in which it is measured.

The no-load losses consist primarily of the core loss in the transformer core, which is a function of the magnitude, frequency, and waveform of the impressed voltage. No-load losses also vary with temperature and are particularly sensitive to differences in waveform; therefore, no-load loss measurements will vary markedly with the waveform of the test voltage.

In addition, several other factors affect the no-load losses and current of a transformer. The design-related factors include the type and thickness of core steel, the core configuration, the geometry of core joints, and the core flux density.

Factors that cause differences in the no-load losses of transformers of the same design include variability in characteristics of the core steel, mechanical stresses induced in manufacturing, variation in gap structure, core joints, etc.

8.2 No-load loss test

The purpose of the no-load loss test is to measure no-load losses at a specified excitation voltage and a specified frequency. The no-load loss determination shall be based on a sine-wave voltage, unless a different waveform is inherent in the operation of the transformer. The average-voltage voltmeter method is the most accurate method for correcting the measured no-load losses to a sine-wave basis and is recommended. This method employs two-parallel-connected voltmeters; one is an average-responding (but rms calibrated) voltmeter; the other is a true rms-responding voltmeter. The test voltage is adjusted to the specified value as read by the average-responding voltmeter. The readings of both voltmeters are employed to correct the no-load losses to a sine-wave basis, using Equation (2) in accordance with 8.3.

8.2.1 Connection diagrams

Tests for the no-load loss determination of a single-phase transformer are carried out using the schemes depicted in Figure 12 and Figure 13. Figure 12 shows the necessary equipment and connections for the case where instrument transformers are not required. When instrument transformers are required, which is the general case, the equipment and connections shown in Figure 13 apply. If necessary, correction for losses in connected measurement instruments may be made by disconnecting the transformer under test and noting the wattmeter reading at the specified test circuit voltage. These losses represent the losses of the connected instruments (and voltage transformer, if used). They may be subtracted from the earlier wattmeter reading to obtain the no-load loss of the transformer under test.

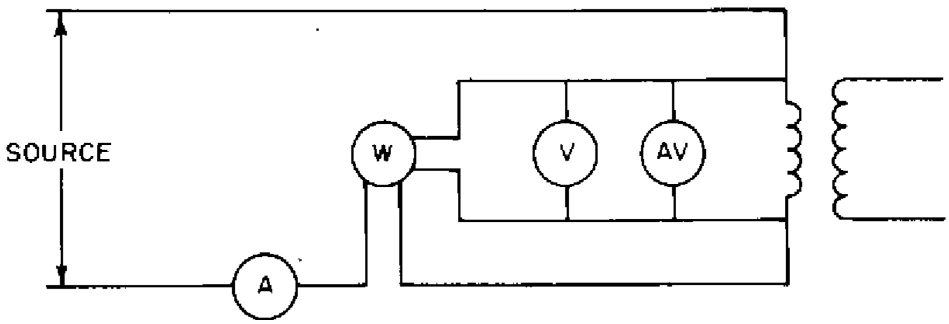


Figure 12—Connections for no-load loss test of a single-phase transformer without instrument transformers

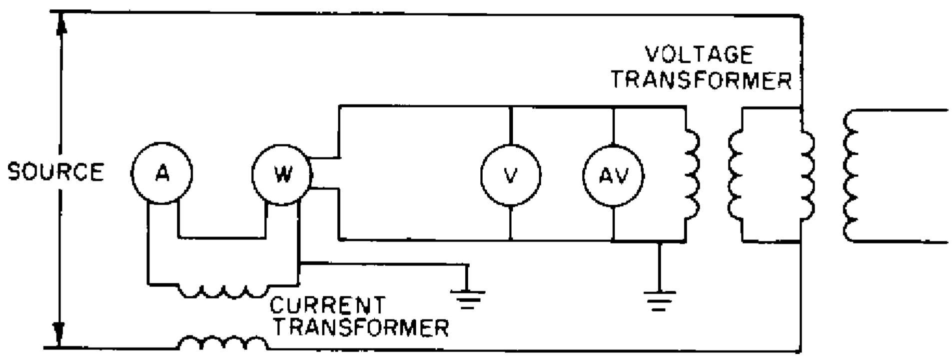


Figure 13—Connections for no-load loss test of a single-phase transformer with instrument transformers

Tests for the no-load loss determination of a three-phase transformer shall be carried out by using the three wattmeter method. Figure 14 is a schematic representation of the equipment and connections necessary for conducting no-load loss measurements of a three-phase transformer when instrument transformers are necessary.

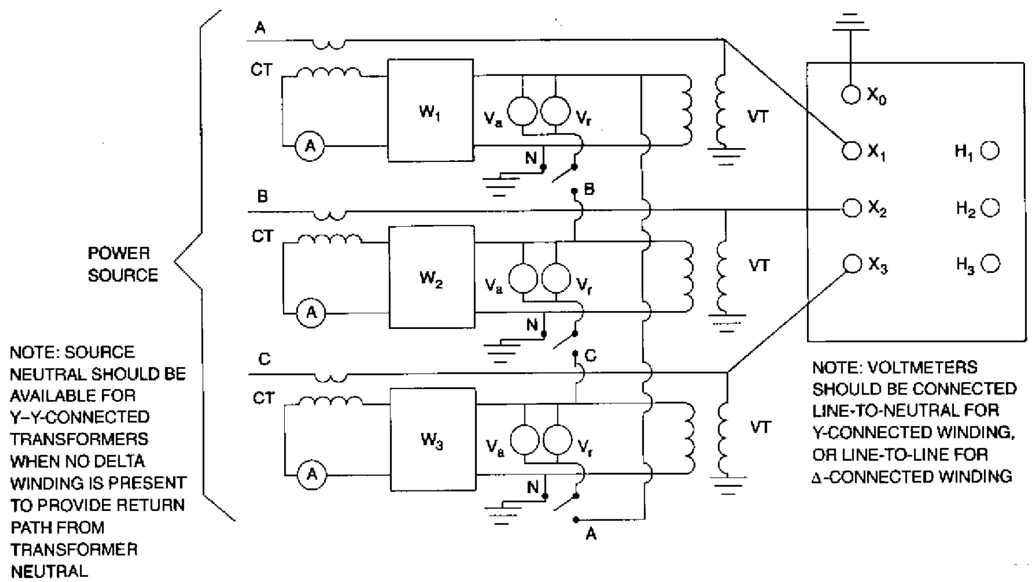


Figure 14—Three-phase transformer connections for no-load loss and excitation current tests using three-wattmeter method

8.2.2 Voltmeter connections

When correcting to a sine-wave basis using the average-voltage voltmeter method, attention must be paid to the voltmeter connections, because the line-to-line voltage waveform may differ from line-to-neutral voltage waveform. Therefore, depending upon whether the transformer windings energized during the test are connected delta or wye, the voltmeter connections shall be such that the waveform applied to the voltmeters is the same as the waveform across the energized windings.

8.2.3 Energized windings

Either the high- or the low-voltage winding of the transformer under test may be energized, but it is generally more convenient to make this test using the low-voltage winding. In any case, the full winding (not merely a portion of the winding) should be used whenever possible. If, for some unusual reason, only a portion of a winding is excited, this portion shall not be less than 25% of the winding.

8.2.4 Voltage and frequency

The operating and performance characteristics of a transformer are based upon rated voltage and rated frequency, unless otherwise specified. Therefore, the no-load loss test is conducted with rated voltage impressed across the transformer terminals, using a voltage source at a frequency equal to the rated frequency of the transformer under test, unless otherwise specified.

For the determination of the no-load losses of a single-phase transformer or a three-phase transformer, the frequency of the test source should be within ±0.5% of the rated frequency of the transformer under test. The voltage shall be adjusted to the specified value as indicated by the average-voltage voltmeter. Simultaneous values of rms voltage, rms current, electrical power, and the average-voltage voltmeter readings shall be recorded. For a three-phase transformer, the average of the three voltmeter readings shall be the desired nominal value.

8.3 Waveform correction of no-load losses

The eddy-current component of the no-load loss varies with the square of the rms value of excitation voltage and is substantially independent of the voltage waveform. When the test voltage is held at the specified value as read on the average-voltage voltmeter, the actual rms value of the test voltage may not be equal to the specified value. The no-load losses of the transformer corrected to a sine-wave basis shall be determined from the measured value by means of the following equation:

$$P_c(T_m) = \frac{P_m}{P_1 + kP_2} \tag{2}$$

where

T_m is the core temperature at the time of test in °C,
$P_c(T_m)$ is the no-load losses, corrected for waveform, at temperature T_m,
P_m is measured no-load losses at temperature T_m,
P_1 is per unit hysteresis loss,
P_2 is per unit eddy-current loss.

$$k = \left(\frac{E_r}{E_a}\right)^2 \tag{3}$$

where

E_r is the test voltage measured by rms voltmeter,
E_a is the test voltage measured by average-voltage voltmeter.

The actual per unit values of hysteresis and eddy-current losses should be used, if available. If actual values are not available, it is suggested that the two loss components be assumed equal in value, assigning each a value of 0.5 per unit.

Equation (2) above is valid only for test voltages with moderate waveform distortion. If waveform distortion in the test voltage causes the magnitude of the correction to be greater than 5%, then the test voltage waveform shall be improved for an adequate determination of the no-load losses and currents.

8.4 Determination of excitation (no-load) current

The excitation (no-load) current of a transformer is the current that maintains the rated magnetic flux excitation in the core of the transformer. The excitation current is usually expressed in per unit or in percent of the rated line current of the winding in which it is measured. (Where the cooling class of the transformer involves more than one kVA rating, the lowest kVA rating is used to determine the base current.) Measurement of excitation current is usually carried out in conjunction with the tests for no-load losses. Rms current is recorded simultaneously during the test for no-load losses using the average-voltage voltmeter method. This value is used in calculating the per unit or percent excitation current. For a three-phase transformer, the excitation current is calculated by taking the average of the magnitudes of the three line currents.

9. Load losses and impedance voltage

9.1 General

The load losses of a transformer are those losses incident to a specified load carried by the transformer. Load losses include I^2R loss in the windings due to load current, I^2R loss in the leads or bus bar due to load current, and stray losses due to eddy currents induced by leakage flux in the windings, leads or bus bar, core clamps, magnetic shields, tank walls, and other conducting parts. Stray losses may also be caused by circulating currents in parallel windings or strands. Load losses are measured by applying a short circuit across either the high-voltage terminals or the low-voltage terminals, and applying sufficient voltage across the other terminals to cause a specified current to flow in the windings. The power loss within the transformer under these conditions equals the load losses of the transformer at the temperature of test for the specified load current.

The impedance voltage of a transformer is the voltage required to circulate rated current through one of two specified windings and associated leads or bus bar when the other winding and associated leads or bus bar is short-circuited, with the windings connected as for rated voltage operation. Impedance voltage is usually expressed in per unit, or percent, of the rated voltage of the winding across which the voltage is applied and measured. The impedance voltage comprises a resistive component and a reactive component. The resistive component of the impedance voltage, called the resistance drop, is in phase with the current and corresponds to the load losses. The reactive component of the impedance voltage, called the reactance drop, is in quadrature with the current and corresponds to the leakage-flux linkages of the windings. The impedance voltage is the phasor sum of the two components. The impedance voltage is measured during the load loss test by measuring the voltage required to circulate rated current in the windings and associated leads or bus bar. The measured voltage is the impedance voltage at the temperature of test, and the power loss dissipated within the transformer is equal to the load losses at the temperature of test and at rated load. The impedance voltage and the load losses are corrected to a reference temperature using the formulas specified in this standard.

The impedance kVA is the product of the impedance voltage across the energized winding and associated leads or bus bar in kV times the winding current in amperes. The ratio of the load losses in kW at the temperature of test to the impedance kVA at the temperature of test is the load loss power factor of the transformer during the test.

9.2 Factors affecting the values of load losses and impedance voltage

9.2.1 Design

The design-related factors include conductor material, conductor dimensions, winding design, winding arrangement, leads or bus bar design, leads or bus bar arrangement, shielding design, and selection of structural materials.

9.2.2 Temperature

Load losses are also a function of temperature. The I^2R component of the load losses increases with temperature, while the stray loss component decreases with temperature. Procedures for correcting the load losses and impedance voltage to the standard reference temperature are described in 9.4.1.

9.2.3 Measurements

At low power factors, such as those encountered while measuring the load losses and impedance voltage of power transformers, judicious selection of measurement method and test system components is essential for

accurate and repeatable test results. The phase-angle errors in the instrument transformers, measuring instruments, bridge networks, and accessories affect the load loss test results.

9.3 Tests for measuring load losses and impedance voltage

Regardless of the test method selected, the following preparatory requirements shall be satisfied for accurate test results:

a) To determine the temperature of the windings with sufficient accuracy, the following conditions shall be met. Except as noted below, the three following conditions are necessary:
   1) The temperature of the windings has stabilized.
   2) The temperature of the windings shall be taken immediately before and after the load losses and impedance voltage test in a manner similar to that described in 5.2. The average shall be taken as the true temperature.
   3) The difference in winding temperature before and after the test shall not exceed 5 °C.
b) The conductors used to short-circuit the low-voltage, high-current winding of a transformer shall have a cross-sectional area equal to or greater than the corresponding transformer leads.
c) The frequency of the test source used for measuring load losses and impedance voltage shall be within ±0.5% of the nominal value.

9.3.1 Wattmeter-voltmeter-ammeter method

The connections and apparatus needed for the determination of the load losses and impedance voltage of a single-phase transformer are shown in Figure 15 and Figure 16. Figure 15 applies when instrument transformers are not required. If instrument transformers are required, which is the general case, then Figure 16 applies.

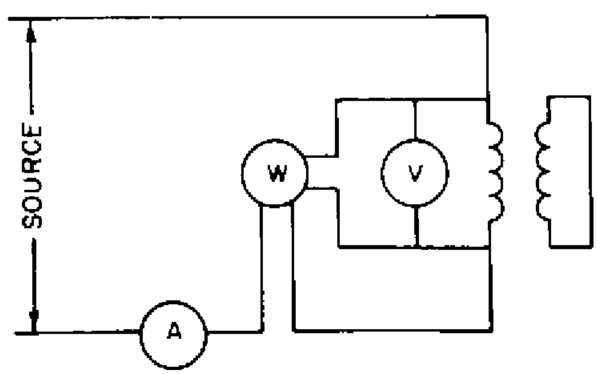


Figure 15—Single-phase transformer connections for load loss and impedance voltage tests without instrument transformers

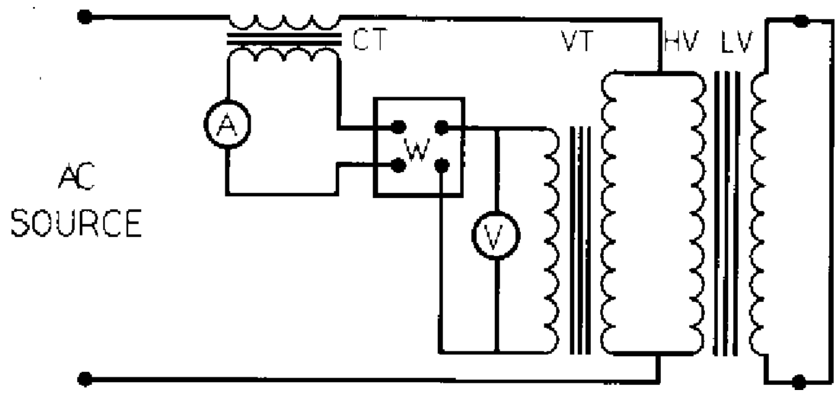


Figure 16—Single-phase transformer connections for load loss and impedance voltage tests with instrument transformers

NOTE—Instrument transformers to be added when necessary.

For three-phase transformers, three-phase power measurement utilizing two wattmeters is possible but can result in very large errors at low power factors encountered in load loss tests of transformers. The two-wattmeter method should not be used for loss tests on three-phase transformers.

For three-phase transformers, Figure 17 shows the apparatus and connections using the three-wattmeter method.

The selection of test method and test system components should be such that the accuracy requirements as specified in IEEE Std C57.12.01-1998 are satisfied.

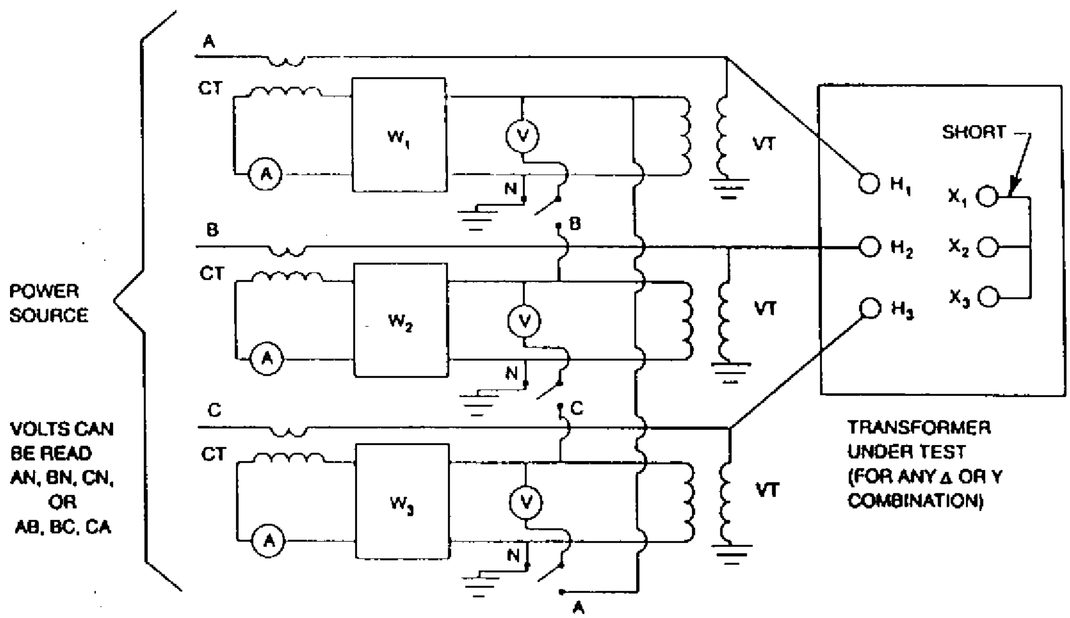


Figure 17—Three-phase transformer connections for load loss and impedance voltage tests using three-wattmeter method

9.3.2 Impedance bridge methods

Impedance bridge methods may be used as an alternate to the wattmeter-voltmeter-ammeter method for measurement of load losses and impedance voltage.

While many configurations of impedance bridge networks are possible, the choice of a particular network is determined by considerations of the measurement environment and available test facility. The general form of the impedance bridge as shown in Figure 18 is an electrical network so arranged that a voltage proportional to the current through the transformer under test is compared with a reference voltage that is a function of the applied voltage E_t. The voltage comparison is made by adjusting one or more of the bridge arms (Z_1, Z_2, and Z_3) until the voltage across Z_2 and Z_3 are exactly equal in magnitude and phase. Voltage balance is indicated by a null reading of the DET. The impedance characteristics of the transformer under test can then be calculated from the values of Z_1, Z_2, and Z_3.

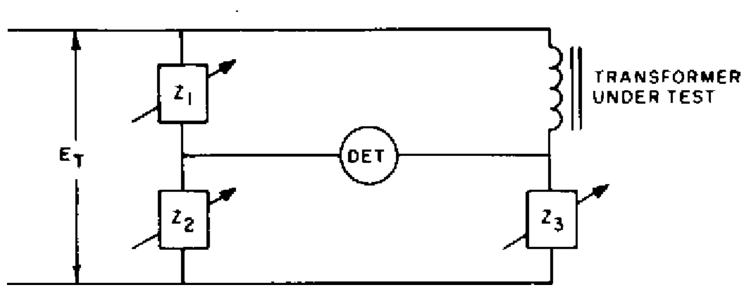


Figure 18—General impedance bridge network

Two of the most commonly used bridge networks for transformer testing are shown in Figure 19 and Figure 20. In Figure 19, a bridge technique is illustrated that employs a precision, low-loss high-voltage capacitor and precision current transformer (CT). It has some similarities to the classical Schering and Maxwell bridges. In Figure 20, another bridge technique employing an HV capacitor, precision CT, and a transformer ratio arm bridge is shown.

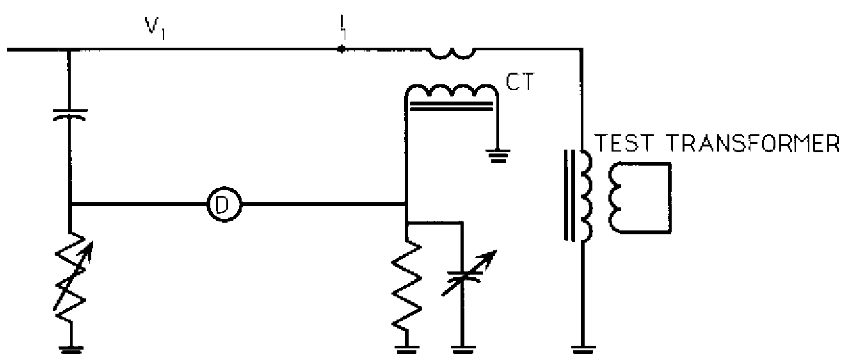


Figure 19—RC-type impedance bridge

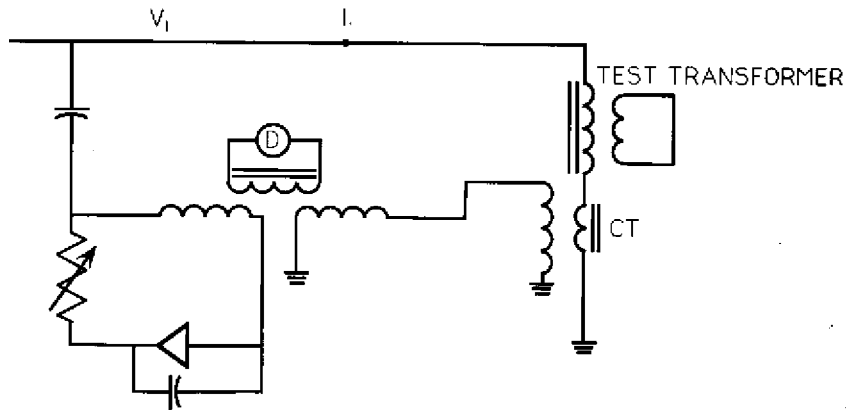


Figure 20—Transformer-ratio-arm bridge

In general, the bridge network adjustments for voltage balance are frequency-dependent; therefore, excitation of the bridge shall be made with a power source that has low harmonic distortion and excellent frequency stability.

The factors that impact overall accuracy of test results by the wattmeter-voltmeter-ammeter method also impact the accuracy of test result by impedance bridge methods.

Loss measurements on three-phase transformers using a three-phase source are made by connecting the bridge network to each phase in turn and calculating the total losses from the three single-phase measurements. This is analogous to the three-wattmeter method of measuring losses by switching a single wattmeter from phase to phase. To verify that switching the bridge from phase to phase does not affect the result on the remaining phases, and to demonstrate that the time involved in switching the bridge does not result in undue heating of the transformer windings during the test, the losses can be monitored for stable readings by wattmeters in all phases.

9.3.3 Transformer test procedures

9.3.3.1 Two-winding transformers and autotransformers

Load loss and impedance voltage tests are carried out using the connections and apparatus shown in Figure 16 for single-phase transformers and Figure 17 for three-phase transformers.

With one winding and associated leads or bus bar short-circuited at the terminals, a voltage of sufficient magnitude at rated frequency is applied to the other winding and associated leads or bus bar at the terminals and adjusted to circulate rated current in the excited winding and associated leads or bus bar. Simultaneous readings of wattmeters, voltmeters, and ammeter are taken. If necessary, the corrections for the losses in external connections and connected measuring instruments should be made.

The procedure for testing three-phase transformers is very similar, except that all connections and measurements are three-phase instead of single-phase, and a balanced three-phase source of power is used for the tests. If the three line currents cannot be balanced, their average rms value should correspond to the desired value, at which time simultaneous readings of wattmeters, voltmeters, and ammeter should be recorded.

Single-phase and three-phase autotransformers may be tested with internal connections unchanged. The test is made using the autotransformer connection. The input (or output) terminals are shorted, and voltage (at

rated frequency) is applied to the other terminals. The voltage is adjusted to cause rated line current to flow in the test circuit as shown in Figure 21. Simultaneous readings of wattmeters, voltmeters, and ammeter are recorded for determinations of load losses and impedance voltage.

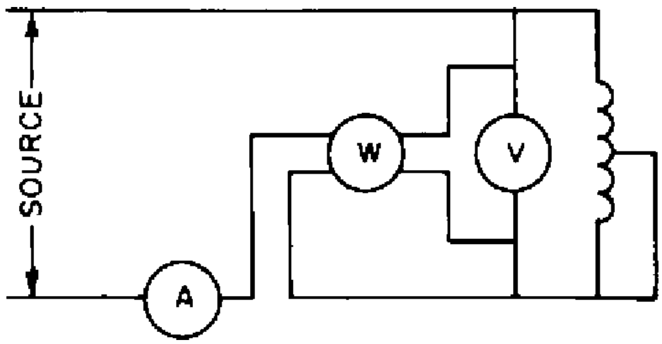


Figure 21—Connections for impedance loss and impedance-voltage tests of an autotransformer

For the purpose of measuring load losses and impedance voltage, the series and common windings of autotransformers may be treated as separate windings—one short-circuited, the other excited. In this situation, where the transformer is connected in the two-winding connection for the test, the current held shall be the rated current of the excited winding, which may or may not be the same as rated line current. The load loss watts and applied voltamperes will be the same, whether series and common windings are treated as separate windings in the two-winding connection or are connected in the autotransformer connection—so long as rated winding current is held in the first case and rated line current in the second case.

9.3.3.2 Three-winding transformer

For a three-winding transformer, which may be either single-phase or three-phase, three sets of impedance measurements are made between pairs of windings and associated leads or bus bar at the terminals, following the same procedure as for two-winding transformers. Measurements of the impedances Z_{12}, Z_{23}, and Z_{31} are obtained between windings 1, 2, and 3.

If the kVA capacities of the different windings are not alike, the current held for the impedance test should correspond to the capacity of the lower-rated winding of the pair of windings under test. However, all of these data when converted into percentage form should be based on the same output kVA, preferably that of the primary winding. An equivalent three-winding impedance network as shown in Figure 22 can be derived from the following equations:

$$Z_1 = \frac{Z_{12} - Z_{23} + Z_{31}}{2} \tag{4}$$

$$Z_2 = \frac{Z_{23} - Z_{31} + Z_{12}}{2} = Z_{12} - Z_1 \tag{5}$$

$$Z_3 = \frac{Z_{31} - Z_{12} + Z_{23}}{2} = Z_{31} - Z_1 \tag{6}$$

where

Z_{12}, Z_{23}, and Z_{31} are the measured impedance values between pairs of windings, as indicated, all expressed on the same kVA base.

These equations involve complex numbers, but they may be used for the resistance (in-phase) component or the reactance (quadrature) component of the impedance voltage or of the impedance voltamperes.

The treatment of the individual load losses and impedance voltages for temperature corrections, etc., is the same as for two-winding, single-phase transformers.

The total load losses of a three-winding transformer is the sum of the losses in the branches of the equivalent circuit of Figure 22 for any specific terminal load conditions.

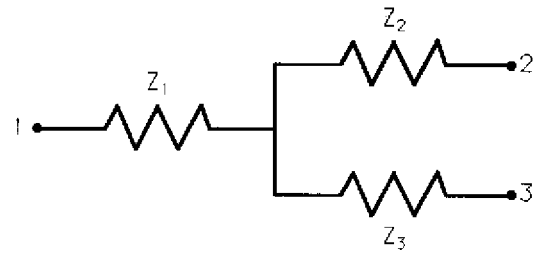


Figure 22—Equivalent three-winding impedance network

9.3.3.3 Interlacing impedance voltage of a Scott-connected transformer

The interlacing impedance voltage of Scott-connected transformers is the single-phase voltage applied from the midtap of the main transformer winding to both ends, connected together. The voltage is sufficient to circulate, in the supply lines, a current equal to the rated three-phase line current. The current in each half of the winding is 50% of this value.

The percent interlacing impedance is the measured voltage expressed as a percent of the teaser voltage. The percent resistance is the measured losses expressed as a percentage of the rated kVA of the teaser winding.

9.3.3.4 Test of three-phase transformer with single-phase voltage

To determine the load losses and impedance voltage of a three-phase transformer with single-phase voltage, the setup, as schematically shown in Figure 23 is recommended.

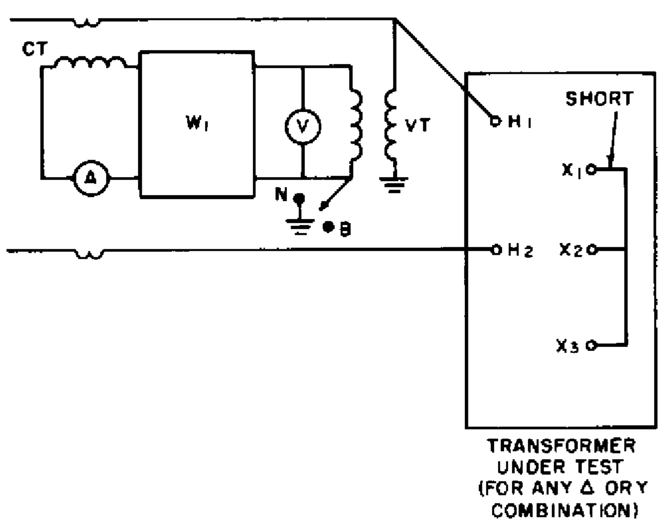


Figure 23—Test of three-phase transformer with single-phase voltage

The three line leads of one winding are short-circuited, and single-phase voltage at rated frequency is applied to two terminals of the other winding. The applied voltage is adjusted to circulate rated line current.

Three successive readings are taken on the three pairs of leads; for example, H_1 and H_2, H_2 and H_3, H_3 and H_1. Then

$$\text{Measured load losses (watts)} = 1.5\left(\frac{(P_{12} + P_{23} + P_{31})}{3}\right) \tag{7}$$

$$\text{Measured impedance voltage} = 0.866\left(\frac{(E_{12} + E_{23} + E_{31})}{3}\right) \tag{8}$$

where

P and E are individual readings of measured load losses and impedance voltage, respectively, as indicated by subscripts.

The stray loss component shall be obtained by subtracting the I^2R losses from the measured load losses of the transformer. Let R_1 be the resistance measured between two high-voltage terminals and R_2 that between two low-voltage terminals; let I_1 and I_2 be the respective rated line currents. Then, the total I^2R loss of all three phases will be

$$\text{Total} I^2R(\text{watts}) = 1.5(I_1{}^2R_1 + I_2{}^2R_2) \tag{9}$$

This formula applies equally well to wye- or delta-connected windings.

Temperature correction shall be made as in 9.4.1.

9.4 Calculation of load losses and impedance voltage from test data

Load losses and impedance voltage measurements vary with temperature and, in general, shall be corrected to a reference temperature.

9.4.1 Temperature correction of load losses

Both I^2R losses and stray losses of a transformer vary with temperature. The I^2R losses, $P_r(T_m)$, of a transformer are calculated from the ohmic resistance measurements (corrected to the temperature, T_m, at which the measurement of load losses and impedance voltage was done) and the current that was used in the impedance measurement. These I^2R losses subtracted from the measured load loss watts, $P(T_m)$, give the stray losses, $P_s(T_m)$, of the transformer at the temperature at which the load loss test was made.

$$P_s(T_m) = P(T_m) - P_r(T_m) \tag{10}$$

where

$P_s\ (T_m)$ is the calculated stray losses (watts) at temperature T_m,
$P\ (T_m)$ is the transformer load losses (watts),
$\mathrm{P}_r\ (\mathrm{T}_m)$ is the calculated I^2R loss (watts) at temperature T_m.

The I^2R component of load losses increases with temperature. The stray loss component diminishes with temperature. Therefore, when it is desirable to convert the load losses from the temperature at which it is measured, T_m, to another temperature, T, the two components of the load losses are corrected separately.

Thus,

$$P_r(T) = P_r(T_m)\left(\frac{T_k + T}{T_k + T_m}\right) \tag{11}$$

$$P_s(T) = P_s(T_m)\left(\frac{T_k + T_m}{T_k + T}\right) \tag{12}$$

then

$$P(T) = P_r(T) + P_s(T) \tag{13}$$

where

$P_r(T)$ is the I^2R loss (watts) at temperature T, °C,
$P_s(T)$ is the stray losses (watts) at temperature T, °C,
$P(T)$ is the transformer load losses (watts) corrected to temperature T, °C,
T_k is 234.5 °C (copper),
T_k is 225 °C (aluminum) (see note below).

NOTE—For pure EC aluminum, 225 applies. T_k may be as high as 240 °C for alloyed aluminum. Where copper and aluminum windings are employed in the same transformer, a value for T_k of 229 °C should be applied for the correction of stray losses.

9.4.2 Impedance voltage

Impedance voltage and its resistive and reactive components are determined by the use of the following equations:

$$E_r(T_m) = \frac{P(T_m)}{I} \tag{14}$$

$$E_x = \sqrt{E_z(T_m)^2 - E_r(T_m)^2} \tag{15}$$

$$E_r(T) = \frac{P(T)}{I} \tag{16}$$

$$E_z(T) = \sqrt{E_r(T)^2 + E_x^2} \tag{17}$$

where

$E_r(T_m)$ is the resistance voltage drop (V) of in-phase component at temperature, T_m,
$P(T_m)$ is transformer load losses (W) measured at temperature, T_m,
I is the current (A) in excited winding,
E_x is the reactance voltage drop (V) of quadrature component,
$E_z(T_m)$ is the impedance voltage (V) at temperature, T_m,
$P(T)$ is the transformer load losses (W) corrected to temperature, T,
$E_r(T)$ is the resistance voltage drop (V) of in-phase component corrected to temperature, T,
$E_z(T)$ is the impedance voltage (V) at temperature, T.

Per unit values of the resistance, reactance, and impedance voltage are obtained by dividing $E_r(T)$, E_x, and $E_z(T)$ by the rated voltage. Percentage values are obtained by multiplying per-unit values by 100.

9.5 Zero-phase-sequence impedance

9.5.1 Zero-phase-sequence impedance tests of three-phase transformers

The zero-phase-sequence impedance characteristics of three-phase transformers depend upon the winding connections, and in some cases, upon the core construction. Zero-phase-sequence impedance tests described in this standard apply only to transformers having one or more windings with a physical neutral brought out for external connection. In all tests, one such winding shall be excited at rated frequency between the neutral and the three line terminals connected together. External connection of other windings shall be as described in succeeding subclauses for various transformer connections. Transformers with connections other than as described in succeeding subclauses shall be tested as determined by those responsible for design and application.

The excitation voltage and current shall be established as follows. If no delta connection is present on the transformer, the applied voltage should neither exceed 30% of the rated line-to-neutral voltage of the winding being energized, nor should the phase current exceed its rated value. If a delta connection is present, the applied voltage should be such that the rated phase current of any delta winding is not exceeded. The percent excitation voltage at which the tests are made shall be shown on the test report. The time duration of the test shall be such that the thermal limits of any of the transformer parts are not exceeded.

Single-phase measurements of excitation voltage, total current, and power shall be similar to those described in 9.3. The zero-phase-sequence impedance, in percent, on kVA base of excited winding for the test connection is

$$Z_o(\%) = 300\left(\frac{E}{E_r} \times \frac{I_r}{I}\right) \qquad (18)$$

where

- E is the measured excitation voltage,
- E_r is the rated phase-to-neutral voltage of excited winding,
- I_r is the rated current per phase of the excited windings,
- I is the measured total input current flowing in the three parallel-connected phases.

9.5.2 Transformers with one neutral externally available, excluding transformers with interconnected windings

The zero-phase sequence network giving the external characteristics for transformers of this type is shown in Figure 24. Winding 1 has the available neutral, while windings 2, 3, etc. do not.

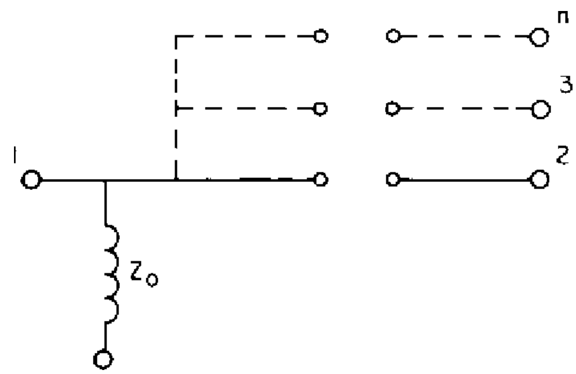


Figure 24—Equivalent zero-phase-sequence network for transformers with one externally available neutral

A zero-sequence test shall be made on the winding with the available neutral. A single-phase voltage shall be applied between the three shorted line terminals and neutral. The external terminals of all other windings may be open-circuited or shorted and grounded.

The term *interconnected windings* shall be interpreted to mean windings in which one or more electrical phases are linked by more than one magnetic phase.

9.5.3 Transformers with two neutrals externally available, excluding transformers with interconnected windings

The zero-phase sequence network giving the external characteristics for transformers of this type is shown in Figure 25. Windings 1 and 2 have the externally available neutrals while windings 3, 4, etc. do not. The diagram is drawn for the case of 0 degrees phase shift between windings 1 and 2.

NOTE—Applies also to autotransformers.

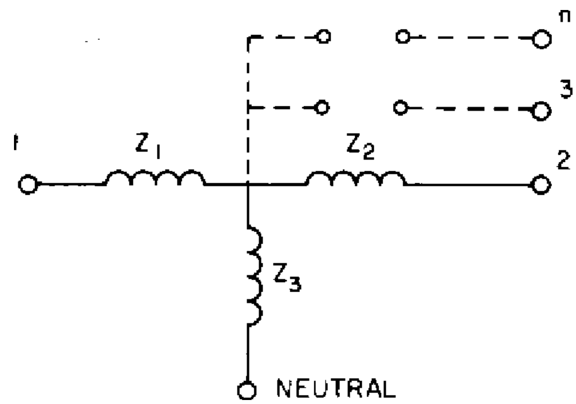


Figure 25—Equivalent zero-phase-sequence network for transformers with two externally available neutrals and 0 degrees phase shift between windings 1 and 2

The following four tests may be made to determine the zero-phase-sequence equivalent network, one of which is redundant:

a) *Test 1*. Apply a single-phase voltage to winding 1 between the shorted line terminals of winding 1 and its neutral. All other windings are open-circuited. The measured zero-phase-sequence impedance is represented by Z_{1NO}.

b) *Test 2*. Apply a single-phase voltage to winding 2 between the shorted line terminals of winding 2 and its neutral. All other windings are open-circuited. The measured zero-phase-sequence impedance is represented by Z_{2NO}.

c) *Test 3*. Apply a single-phase voltage to winding 1 between the shorted line terminals of winding 1 and its neutral. Short the line terminals and neutral of winding 2. All other windings may be open-circuited or shorted. The measured zero-sequence impedance is represented by Z_{1Ns}.

d) *Test 4*. Apply a single-phase voltage to winding 2 between the shorted line terminals of winding 2 and its neutral. Short the line terminals and neutral of winding 1. All other windings may be open-circuited or shorted. The measured zero-phase-sequence impedance is represented by Z_{2Ns}.

Test 4 is redundant to Test 3 and need not be performed. If performed, however, it may be used as a check.

All measured zero-phase-sequence impedances should be expressed in percent and placed on a common kVA base. The constants in the equivalent circuit are the following:

$$
\begin{aligned}
Z_3 &= +\sqrt{Z_{2NO} \times (Z_{1NO} - Z_{1Ns})} = +\sqrt{Z_{1(NO)} \times (Z_{2(NO)} - Z_{2Ns})} \\
Z_2 &= Z_{2NO} - Z_3 \\
Z_1 &= Z_{1NO} - Z_3
\end{aligned}
\tag{19}
$$

NOTE—These equations involve complex numbers. The plus sign before the radical in the first equation above is appropriate for most common cases in which windings 1 and 2 are physically adjacent in the design, and no delta winding (3, 4, etc.) is interleaved with them. A minus sign may be appropriate when a delta winding (3 or 4) is physically located within or between windings 1 and 2. The correctness of the sign can be checked by comparison with design calculations of zero-sequence impedance.

If Z_{1NO} and Z_{2NO} approach infinity, then Z_3 approaches infinity, and the equivalent circuit is that shown in Figure 26.

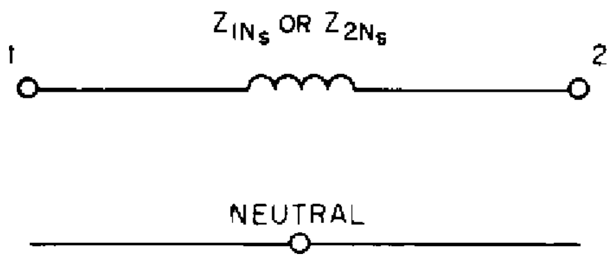


Figure 26—Equivalent zero-phase-sequence network for transformers with two externally available neutrals and 0 degrees phase shift if Z_{1NO} and Z_{2NO} approach infinity

In the case of wye-wye connected transformers, the zero-sequence impedance, in general, is a nonlinear function of the applied voltage, which, in turn, may require more than one set of measurements to characterize the nonlinear behavior.

9.5.4 Autotransformers

The tests and equivalent circuits of 9.5.2 and 9.5.3 apply equally well for autotransformer connections, except that the externally available neutral of a common winding should be considered as two externally available neutrals, one for the common winding and one for the series-common combination.

10. Dielectric tests

10.1 Factory dielectric tests

10.1.1 Purpose

The purpose of dielectric tests in the factory is to demonstrate that the transformer has been designed and constructed to withstand the imposition of voltages associated with the specified insulation levels.

10.1.2 Test voltages

Unless otherwise specified, the dielectric test voltages shall be measured or applied, or both, in accordance with IEEE Std 4-1995.

10.1.3 Transformers

Transformers shall be assembled prior to making dielectric tests, including sheet metal enclosures and any terminal compartments involved, except in those instances where the transformer is furnished to the user without sheet metal enclosures or terminal compartments.

10.1.4 Temperature

The temperature of the transformer during dielectric testing shall be between 10 °C and 40 °C.

10.1.5 Conditions

The dielectric tests specified in 10.1.5.1 through 10.1.5.3 shall be performed in accordance with the requirements in IEEE Std C57.12.01-1998.

10.1.5.1 Low-frequency dielectric tests

Tests shall be performed in accordance with Table 4 and 5.10 of IEEE Std C57.12.01-1998.

NOTES:

1—In the following test descriptions, the word *phase* refers to the *line terminal* of a winding and not to the entire phase of a winding, recognizing the construction of windings with *graded insulation*.

2—The low-frequency tests are described in functional and geometric terms. The accomplishment of these low-frequency tests is achieved by the *applied-voltage* and *induced-voltage* tests described in 10.3 and 10.4, or combinations thereof.

10.1.5.2 Low-frequency tests—exceptions

Exceptions of the low-frequency tests shall occur as follows:

a) Subject to the limitation that the voltage-to-ground test shall be performed as specified in 10.1.5.1 on the line terminals of the winding with the lowest ratio of test voltage to minimum turns, the test levels may otherwise be reduced such that none of the tests required in 10.5.1.1 need be exceeded in order to meet the requirements of the others, or such that no winding need be tested above its specified level in order to meet the test requirements of another winding.
b) Autotransformers with grounded neutrals cannot always be tested at the assigned low-frequency test levels because the insulation levels may not be in proportion to the turns ratio of the windings. In that case, the winding with the lowest ratio of low-frequency test voltage to minimum turns will determine the induced voltages on all windings. The other winding will be tested at maximum turns unless maximum turns will produce a voltage in the other winding in excess of the required test level. This situation is possible on autotransformers with a wide tap-changer range in one winding.

10.1.5.3 Impulse tests

When specified, impulse tests shall be performed in accordance with IEEE Std C57.12.01-1998.

10.1.5.4 Test sequence

The sequence of tests shall be impulse tests (when required) followed by the low-frequency voltage tests.

10.2 Dielectric tests in the field

It is recognized that dielectric tests impose a severe stress on the insulation and, if applied frequently, will hasten breakdown or may cause breakdown; the stress imposed, of course, will be more severe the higher the value of the applied voltage. Hence, practice in this matter has varied widely among operating companies, and the advisability of periodic testing may be questionable.

Field dielectric tests may be warranted by special circumstances. However, periodic dielectric tests are not recommended because of the severe stress imposed on the insulation.

Where low-frequency applied-voltage and induced-voltage tests for acceptance are conducted in the field, the test voltages shall not exceed 75% of factory test values. When field tests are made on a periodic basis, it is recommended that the test voltages be limited to 65% of factory test values.

Duration of the tests shall be the same as that specified in 10.3 and 10.4.

10.3 Applied-voltage tests

10.3.1 Delta-connected windings

For transformers designed for delta connection or designed so that either terminal of a single-phase winding can be used as the line terminal, the applied-voltage test shall be made by applying between each winding and all other windings connected to ground, a low-frequency voltage from an external source, in accordance with Table 5 of IEEE Std C57.12.01-1998.

10.3.2 Wye-connected windings

Permanently wye-connected windings shall receive an applied-voltage test in accordance with 5.10.3.2 and column 2 in Table 5 of IEEE Std C57.12.01-1998, when the neutral is solidly grounded or in accordance with 5.10.2.2 and column 2 in Table 5 when the neutral is ungrounded.

10.3.3 Ground connections during test

A normal power frequency such as 60 Hz shall be used and the duration of the test shall be 1 min. The winding being tested shall have all its parts joined together and connected to the line terminal of the testing transformer. All other terminals and parts (including core and enclosure or tank) shall be connected to ground and to the grounded terminal of the testing transformer.

The ground connections between the apparatus being tested and the testing transformer shall be a substantial metallic circuit. All connections shall make good mechanical joints without forming sharp corners or points. Small bare wire may be used in connecting the respective taps and line terminals together, but care shall be taken to keep the wire on the high-voltage side well away from the ground. No appreciable resistance should be placed between the testing transformer and the one under test. It is permissible, however, to use reactive coils at or near the terminals of the testing transformer. A relief gap set at a voltage 10% or more in excess of the specified test voltage may be connected during the applied-voltage test.

10.3.4 Voltage rate of rise

The voltage should be started at one-quarter or less of the full value and be brought up gradually to full value in not more than 15 s. After being held for the time specified, it should be reduced gradually (in not more than 5 s) to one-quarter of the maximum value or less, and the circuit opened.

10.4 Induced-voltage tests

10.4.1 Terminals

The induced-voltage test for transformers that receive the full standard applied-voltage test shall be made by applying a voltage between the terminals of one winding as specified in 5.10.3.2 of IEEE Std C57.12.01-1998.

10.4.2 Duration

The induced-voltage test shall be applied for 7200 cycles or 60 s, whichever is shorter.

10.4.3 Frequency

As this test applies greater than rated voltage per turn to the transformer, the frequency of the applied voltage shall be high enough to limit the flux density in the core to that permitted by 4.1.6 of IEEE Std C57.12.01-1998. The minimum test frequency to meet this condition is as follows:

$$\text{Test frequency} = \frac{E_t}{1.1E_r} \times (\text{rated frequency}) \tag{20}$$

where

E_t is the induced test voltage across the winding,
E_r is the rated voltage across the winding.

10.4.4 Rate of rise of voltage

The voltage should be started at one-quarter or less of the full value and be brought up gradually to full value in not more than 15 s. After being held for the time specified in 10.4.2, it should be reduced gradually (in not more than 5 s) to one-quarter of the maximum value or less, and the circuit opened.

10.4.5 Transformers having one end of the high-voltage winding grounded

In the case of transformers having one end of the high-voltage winding grounded, the other windings should be grounded during the induced-voltage test. This ground on each winding may be made at a selected point of the winding itself or of the winding of a set-up transformer, which is used to supply the voltage, or which is connected for the purpose of furnishing the ground.

10.4.6 Transformers with reduced neutral insulation

Three-phase wye-connected transformers with reduced neutral insulation shall have the neutral grounded during the induced-voltage test and shall be tested with three-phase induced voltage.

10.4.6.1 Neutral grounding options

Three-phase wye-connected transformers with nonreduced neutral insulation may be tested with the neutral either grounded or ungrounded.

10.4.6.2 An alternate method

An alternate method of making the induced-voltage test may be used with single-phase excitation. This is done by short-circuiting one phase at a time of the high-voltage winding and exciting the remaining two phases to achieve twice-rated turn-to-turn voltage in the excited windings. Three tests, one for each phase, are required.

NOTE—This alternate method will result in approximately 15% excess voltage between line terminals.

10.4.7 Avoiding excess voltage induced in other windings

When the induced test on a winding results in a voltage between terminals of other windings in excess of the low-frequency test voltage specified in these standards, the other winding may be sectionalized and grounded. Additional induced tests shall then be made to give the required test voltage between terminals of windings that were sectionalized.

10.4.8 Monitoring current

The current should be monitored simultaneously on each line terminal being excited during the induced test. Any abrupt change should be investigated.

10.5 Impulse tests

NOTE—See IEEE Std C57.98-1993 for information on impulse testing techniques, interpretation of oscillograms, and failure detection criteria.

10.5.1 General

When required, the impulse test shall precede the low-frequency applied-voltage and induced-voltage tests. Impulse tests consist of applying, in the following order, one reduced full wave, two chopped waves, and one full wave. Applicable values are listed in IEEE Std C57.12.01-1998 or in applicable product standards.

a) *Reduced full-wave test*. For this test, the applied voltage wave shall have a crest value of between 50% and 70% of the required full-wave value.
b) *Chopped-wave test*. For this test, the applied voltage wave shall be chopped by a suitable air gap. It shall have a crest value and time to flashover in accordance with Table 5 of IEEE Std C57.12.01-1998. The gap shall be located as close as possible to the terminals, and the impedance shall be limited to that of the necessary leads to the gap.
c) *Full-wave test*. For this test, the voltage wave shall have a crest value in accordance with Table 5 of IEEE Std C57.12.01-1998, and no flashover of insulated parts or test gap shall occur. During the full-wave test, the voltage level shall be subject to a tolerance of ±3% of the specified BIL level. The tolerance on time to crest shall be subject to ±30% and the time to half crest shall be subject to a tolerance of ±20%.

10.5.1.1 Time interval for tests

The time interval between application of the last chopped wave and the final full wave shall be minimized to avoid recovery of insulation strength if a failure occurs prior to the final full wave.

10.5.1.2 Reporting impulse tests

When impulse tests are required, they shall be reported on the transformer impulse test report form illustrated in IEEE Std C57.98-1993.

10.5.2 Wave to be used for impulse tests

A 1.2/50 µs wave shall be used for full-wave and reduced full-wave tests. Waves of positive polarity shall be used for dry-type transformers. The time to crest on the front from virtual time zero to actual crest shall not exceed 2.5 µs except for windings of large impulse capacitance (e.g., low-voltage; high-kVA and some high-voltage; high-kVA windings).

To demonstrate that the large impulse capacitance of the winding causes the long front, the impulse generator series resistance may be reduced, which should cause superimposed oscillations. Only the inherent generator and lead inductances should be in the circuit.

For convenience in measurement, the time to crest may be considered as 1.67 times the actual time between points on the front of the wave at 30% and 90% of the crest value.

The time on the tail to the point of half-crest voltage of the applied wave shall be not less than 40 µs from the virtual time zero, unless the winding is of low inductance. This is within the –20% tolerance provided for a 1.2/50 µs wave.

The virtual time zero can be determined by locating points on the front of the wave at which the voltage is, respectively, 30% and 90% of the crest value and then drawing a straight line through these points. The intersection of this line with the zero voltage line is the virtual time zero.

When there are high-frequency oscillations on the crest of the wave, the crest value shall be determined from a smooth wave sketched through the oscillations. If the period of these oscillations is 2 µs or more, the actual crest value shall be used.

If there are oscillations on the front of the waves, the 30% and 90% points shall be determined from the average, smooth-wave front sketched in through the oscillations. The magnitude of the oscillations preferably should not exceed 10% of the applied voltage.

All impulses applied to a transformer should be recorded by a cathode-ray oscillograph, or by a suitable recording device such as a digital storage scope, if their crest voltage exceeds 40% of the full-wave value given in the tables in these standards. When reports require oscillograms, those of the first reduced-full-wave voltage and current, the last two chopped waves, and the last full wave of voltage and current shall represent a record of the successful application of the impulse test to the transformer.

10.5.3 Connections for impulse tests

In general, the tests shall be applied to each terminal, one at a time.

10.5.3.1 Grounding

One terminal of the winding under test shall be grounded directly or through a low resistance if current measurements are to be made (for exceptions, see the following paragraph). The terminals of windings that are not being tested may be grounded directly or through a resistor in order to limit the voltage induced in these windings. It is desirable that the voltages on terminals that are not being tested should not exceed 80% of the full-wave voltage for their insulation level.

All grounds shall be direct, except as described in the preceding paragraph and at neutral terminals, which may be grounded through the same neutral grounding impedance as is to be used in service. If such neutral grounding impedance is unavailable, the neutral shall be directly grounded.

10.5.3.2 Series/multiple connections

Only the series connection of a series or multiple connection shall be tested unless tests on both connections are specified. The connection of the other windings (whether series or parallel) shall be made at the choice of the manufacturer.

10.5.3.3 Delta- and wye-connections

Unless otherwise specified, tests shall be made on the delta-connection. When so specified, tests shall be made on the wye-connection or both the delta-and wye-connections.

10.5.3.4 Tap connections

Tap connections shall be made with minimum effective turns in the winding under test. The choice of tap connections of windings not being tested shall be made by the manufacturer.

10.5.3.5 Protective devices

When protective devices are permanently connected as an integral part of series transformer windings or of other portions of windings, these devices shall be connected during test. The operation of these devices usually will cause differences between the reduced-full-wave and the full-wave oscillograms. That these differences are caused by the operation of the protective devices may be demonstrated by making two or more reduced-full-wave tests at different voltage values to show the trend in their operation. Further evidence that the differences are due to the operation of the protective devices may be obtained, in some cases, by making additional tests with the protective devices shorted out.

10.5.3.6 Low-impedance windings

In some cases the inductance of the winding is so low that the desired voltage magnitude and duration to the 50% point on the tail of the wave cannot be obtained with available equipment. In some cases, the terminals of such windings having the same insulation class at both ends may be tied together for the test. Because of the difference in insulation level at the two terminals of the winding, it is sometimes impossible to tie the terminals together for the impulse test. Low-inductance windings may also be tested by inserting a resistor of not more than 500 Ω in the grounded end of the winding. In all such cases, shorter waves may be used.

10.6 Impulse tests on transformer neutrals

When specified, impulse tests on the neutral of a transformer may be applied by the methods given in 10.6.1 and 10.6.2. The choice of the method of testing the neutral shall be made by the manufacturer.

NOTE—The standard neutral insulation, specified in IEEE Std C57.12.01-1998, provides for grounded wye-operation, and the neutral is designed for an applied-voltage test. If specified, the neutral shall be insulated for a higher insulation level.

10.6.1 Application to line terminal

The test on the neutral, or neutral and regulating winding, is induced by the application of an impulse to any line terminal with the neutral grounded through a suitable impedance so that the required full-wave test voltage is obtained from the neutral terminal to ground. One reduced and two full waves shall be applied to the line end of a winding with a crest voltage equal to or less than the full-wave level of the line end. The other

windings may be short-circuited for this test. The winding being tested shall be on the maximum voltage connection. The voltage oscillograms shall be taken at the neutral. When this method of test is used, the test on the neutral shall precede the test on the line terminal.

10.6.2 Application directly to the neutral

One reduced and two full waves are applied directly to the winding neutral with an amplitude equal to the BIL of the neutral. The winding being tested shall be on the maximum-voltage connection.

10.7 Detection of failure during impulse test

Because of the nature of impulse test failures, one of the most important matters is the detection of such failures. There are a number of indications of insulation failure.

10.7.1 Ground-current oscillograms

Unless otherwise specified, ground-current oscillograms shall be the preferred method of failure detection, where applicable. Both ground-current oscillograms and voltage oscillograms may be used for failure detection. In this method of failure detection, the impulse current in the grounded end of the winding tested is measured by means of a cathode-ray oscillograph, or another suitable recording device such as a digital storage scope, connected across a suitable shunt inserted between the normally grounded end of the winding and ground. Any differences in the wave shape between the reduced full wave and final full wave detected by superimposing the two current oscillograms may be indications of failure or deviations due to noninjurious causes. They should be fully investigated and explained by a new reduced-wave and full-wave test. Examples are operation of protective devices, core saturation, or conditions in the test circuit external to the transformer. In air- or gas-insulated apparatus, partial discharges (corona) may produce high-frequency oscillations on the wave. This is not an indication of failure and should be taken into account in interpreting the traces.

10.7.1.1 Chopped-wave test

The ground-current method of detection is not applicable for use with chopped-wave tests because of variations due to time of chopping.

10.7.2 Other methods of failure detection

10.7.2.1 Voltage oscillograms

Any unexplained differences between the reduced full wave and the final full wave detected by superimposing the two voltage oscillograms, or any such differences observed by comparing the chopped waves to each other and to the full wave up to the time of flashover, are indications of failure. Deviations may be caused by conditions in the test circuit external to the transformer or by protective devices, and should be fully investigated. In air- or gas-insulated apparatus, partial discharges (corona) may produce high-frequency oscillations on the wave. This is not an indication of failure and should be taken into account in interpreting the traces.

10.7.2.2 Failure of gap to flashover

In making the chopped-wave test, failure of the chopping gap, or any external part, to flashover, although the voltage oscillogram shows a chopped wave, is a definite indication of a flashover either within the transformer or in the test circuit.

10.7.2.3 Noise

Unusual noise within the transformer at the instant of applying the impulse is an indication of trouble. Such noise should be investigated.

10.8 Insulation-power-factor tests

Insulation power factor is the ratio of the power dissipated in the insulation in watts to the product of the effective voltage and current in volt-amperes when tested under a sinusoidal voltage and prescribed conditions.

The methods described herein are applicable to dry-type distribution and power transformers of present-day design.

10.8.1 Preparation for tests

The test specimen shall have

a) All windings short-circuited,
b) All terminals in place, and
c) Temperature of the transformer near the reference temperature of 20 °C.

10.8.2 Instrumentation

Insulation power factor may be measured by special bridge circuits or by the volt-ampere-watt method. The accuracy of the measurement should be within ±0.25%. The measurement should be made at a frequency of 60 Hz, ±0.1 Hz.

10.8.3 Applied voltage

The voltage to be applied for measuring insulation power factor shall not exceed operating voltage to ground for any part of the winding or 1000 V, whichever is lower.

10.8.4 Procedure

Insulation power-factor tests shall be made from windings to ground and between windings, as shown in Table .

Table 1—Measurements to be made in insulation power factor tests

Method I: **Test without guard circuit**[a]	**Method II:** **Test with guard circuit**[a]
Two-winding transformers[b] • High to low and ground • Low to high and ground • High and low to ground	Two-winding transformers[b] • High to low and ground • High to ground, guard on low • Low to high and ground • Low to ground, guard on high

[a]The term *guard* signifies one or more conducting elements arranged and connected on an electrical instrument or measuring circuit so as to divert unwanted currents from the measuring means.
[b]Permanently connected windings, such as autotransformers, shall be considered as one winding.

NOTE—While the real significance that can be attached to the insulation-power-factor of dry-type transformers is still a matter of opinion, experience has shown that insulation power factor is helpful in assessing the probable condition of the insulation when good judgment is used. In interpreting the results of insulation-power-factor test values, the comparative values of tests taken at periodic intervals are useful in identifying potential problems rather than an absolute value of insulation power factor. A factory insulation-power-factor test will be of value for comparison with field insulation power factor measurements to assess the probable condition of the insulation. It has not been feasible to establish standard insulation power factor values for dry-type transformers because experience has indicated that little or no relation exists between insulation power factor and the ability of the transformer to withstand the prescribed dielectric tests.

10.9 Insulation-resistance tests

Insulation-resistance tests are made to determine the insulation resistance from individual windings to ground or between individual windings. The insulation resistance in such tests is commonly measured in megohms but may be calculated from measurements of applied voltage and leakage current.

Insulation-resistance tests shall be made when specified. The insulation resistance of electrical apparatus is of doubtful significance as compared with the dielectric strength. It is subject to wide variation with design, temperature, dryness, and cleanliness of the parts. When the insulation resistance falls below prescribed values, it can, in most cases, if it is of good design and has no defect, be brought up to the prescribed value by cleaning and drying the apparatus. The insulation resistance, therefore, may afford a useful indication as to whether the apparatus is in suitable condition for application of the dielectric test.

NOTES:

1—The significance of values of insulation-resistance tests generally requires some interpretation, depending on the design, dryness, and cleanliness of the insulation involved. If a user decides to make insulation-resistance tests, it is recommended that insulation-resistance values be measured periodically (during maintenance shutdown) and that these periodic values be plotted. Substantial variation in the plotted values of insulation resistance should be investigated for cause.

2—Insulation resistances may vary with applied voltage, and any comparison must be made with measurements at the same voltage.

10.9.1 Preparation for test

Prior to measuring insulation resistance, the following conditions shall be met:

a) Windings in their normal insulation environment
b) All windings short-circuited
c) All bushings or terminals in place
d) Transformer temperature approximately 20 °C

10.9.2 Instrumentation

Insulation resistance may be measured using either of the following:

a) A variable-voltage dc power supply with means to measure voltage and current (generally in microamperes or milliamperes)
b) A megohmeter

NOTE—Megohmeters are commonly available with nominal voltages of 500 V, 1000 V, and 2500 V. DC applied test equipment is available at higher voltages.

10.9.3 Voltage to be applied

The dc voltage applied for measuring insulation resistance to ground shall not exceed a value equal to the rms low-frequency applied voltage allowed in 10.3.

NOTES:

1—Partial discharges should not be present during insulation-resistance tests since they can damage a transformer and may also result in erroneous values of insulation resistance.

2—When measurements are to be made using dc voltages exceeding the rms operating voltage of the winding involved (or 1000 V for a solidly grounded wye winding), a relief gap may be employed to protect the insulation.

10.9.4 Procedure

The procedure for conducting the insulation resistance test shall be as follows:

a) Insulation-resistance tests shall be made with all circuits of equal voltage above ground connected together. Circuits or groups of circuits of different voltages above ground shall be tested separately; for example, high voltage to low voltage and ground, low voltage to high voltage and ground.
b) Voltage should be increased in increments (usually 1–5 kV), holding each step for 1 min.
c) The test should be discontinued immediately in the event the current begins to increase without stabilizing.

10.10 Partial discharge tests

The partial discharge test should be made in accordance with IEEE Std C57.124-1991.

11. Temperature test

11.1 General

The temperature test is defined as a test to determine the temperature rise above the ambient of one or more of the transformer windings, as measured at the terminals. The result for a given terminal pair is an average value of the temperature of the entire circuit and not the temperature at any given point in a specific winding. The term *average winding temperature rise* refers to the value obtained for a given terminal pair. It does not refer to summing the results of different terminal pairs and dividing by the number of pairs to obtain an arithmetic average.

See IEEE Std C57.12.01-1998 for conditions under which temperature limits apply. The transformers shall be tested in the combination of connections and taps that give the highest winding temperature rises as determined by the manufacturer. This will generally involve those connections and taps resulting in the highest losses.

In some cases, temperature testing requires a slight overexcitation. The resultant increase in total loss has a negligible effect on the kilovolt-ampere output. It is therefore not considered in the temperature rise test methods described herein.

The temperature rise tests shall be made in an area that is as free from drafts as practical. All temperature rise tests shall be made under normal conditions and normal means of cooling. When transformers are equipped with fans, two temperature rise tests shall be made. One test shall be at the self-cooled rating and one test shall be at the maximum fan cooled rating.

Transformers shall be completely assembled; however, external switches and air boxes may be omitted and openings around terminals covered with a suitable material to simulate actual arrangements.

It is permissible to shorten the time required for the test by the use of initial overloads, restricted cooling, or any other suitable method. At the end of the temperature rise test, the test current and frequency shall be

within 10% of rated values. Temperature sensors may be thermocouples, thermistors, resistance temperature detectors, thermometers, or other suitable devices. Use of thermocouples is the preferred method of measuring surface temperature.

11.2 Ambient temperature measurements

The ambient temperature shall be taken as that of the surrounding air, which shall not be less than 10 °C or more than 40 °C.

To reduce to a minimum the errors due to time lag between the temperature of the transformer and the variations in the ambient temperature, the temperature sensors shall be placed in suitable containers that shall have such proportions as will require not less than 2 h for the indicated temperature within the container to change 6.3 °C if suddenly placed in air that has a temperature 10 °C higher, or lower, than the previous steady-state indicated temperature within the container.

The ambient temperature shall be the average of the readings from at least three temperature sensors spaced uniformly around the transformer under test. They should be located about one-half the height of the transformer, and at a distance of 0.91–1.83 m from the transformer. They should be protected from drafts, abnormal changes in temperature, and radiant heat from the transformer under test or other sources.

11.3 Surface temperature measurements

Temperature sensors shall be placed in intimate contact with the surface being measured, attached to maintain firm contact, and thermally insulated from the surrounding medium.

For the purpose of determining when constant temperature conditions have been achieved, the temperature sensors shall be applied to the surfaces as specified in the following:

a) Ventilated dry-types—Top center of core top yoke and innermost low-voltage winding lead of middle phase of three-phase units or an inner low-voltage winding lead of a one-phase unit.
b) Sealed dry- or nonventilated types—Center of top cover surface and center of one sidewall surface (an additional quantity is required for the compromise test method per 11.8.6).

Provisions shall be made to measure the surface temperature of iron or alloy parts surrounding or adjacent to the outlet leads or terminals carrying currents in excess of 4000 A. Readings shall be taken at intervals and immediately before shutdown.

The determination of the temperature rise of metal parts within the case, other than winding conductors, is a design test but shall be made when so specified.

11.4 Cold-resistance measurements

Cold-resistance measurements shall be taken on all phases of each primary and secondary winding in accordance with Clause 5. The same test equipment shall be used for both cold- and hot-resistance measurements. Normally, cold-resistance measurements are taken prior to loading the transformer for heat run. If it is discovered that there is a discrepancy in the cold-resistance readings, it is permissible to allow the transformer to cool to ambient temperature and perform the cold-resistance measurements after the loading test. The criteria given in 5.1 shall be met and the cool down time shall be at least 24 h.

11.5 Hot-resistance measurement

The ultimate temperature rise is considered to be reached when the surface temperature rises over ambient become constant; that is, when the temperature rises over ambient, the variation should not be more than 2 °C during a consecutive 3 h period. When the temperature rises become constant, the test voltage and current shall be removed and the fans, if used, shut off.

Hot-resistance measurements shall be taken on all windings of each phase and a cooling curve drawn for each winding of one phase. The first measurement on each phase should be taken as quickly as possible after shutdown, but not before the measuring current has become stable. The first resistance measurement of the winding phase used for the cooling curve must be taken within 6 min.

When transferring leads from one winding to another, the same relative polarity should be maintained with regard to the measuring leads and the transformer terminals.

A recommended sequence of resistance measurements for determination of the hot resistance at shutdown for three-phase delta- and wye-connected transformers is as follows:

a) One secondary resistance measurement on each of three secondary terminals X1-X2, X2-X3, and X3-X1. For wye-connected low voltages, resistance at X1-X0, X2-X0, and X3-X0 terminals may be taken.
b) One resistance measurement on each of three primary terminals H1-H2, H2-H3, and H3-H1. For wye-connected high voltages, resistance at H1-H0, H2-H0, and H3-H0 may be taken.

   The three secondary resistance measurements and one primary resistance measurement should be taken within 6 min.
c) To provide data to plot a resistance time cooling curve, take three additional measurements spaced at least 1 min apart on the primary terminals measured first under step b).
d) To provide data to plot a resistance-time cooling curve, take three additional measurements spaced at least 1 min apart on the secondary terminals measured first under step a).
e) Additional resistance measurements may be taken to improve the accuracy of the resistance time plot.

A similar sequence of resistance measurements should be used for single-phase or multi-winding transformers.

The resistance-time cooling curve shall be extrapolated back to the instant of shutdown by using suitable coordinate paper or computer curve fitting programs. The resistance-time curve obtained on one phase of the primary winding shall be used to determine the correction back to shutdown for the other phases of the primary winding. The resistance-time curve obtained for one phase of the secondary winding shall be used to determine the correction back to shutdown for the other phases of the secondary winding.

If necessary, the temperature test may be resumed and the temperature allowed to stabilize in order to complete the resistance readings within the required time period. For example, all resistance readings for the primary winding, including the cooling curve, may be taken and the temperature test resumed. An additional shutdown is performed and resistance measurements taken including a cooling curve for the secondary winding.

11.6 Calculation of average winding temperature rise

The average winding temperature rise shall be determined from the terminal resistance measurements and reported for each pair of readings (see 11.5).

The average winding temperature of a terminal pair corresponding to a winding phase shall be determined by either of the following equations:

$$T = R/R_o(T_k + T_o) - T_k \tag{21}$$

or

$$T = ((R - R_o)/R_o)(T_k + T_o) + T_o \tag{22}$$

The average winding temperature rise of a terminal pair corresponding to a winding phase shall be determined by the following equation:

$$T_r = T - T_a$$

where

T is the average winding temperature of a terminal pair corresponding to hot resistance, R,
R_o is the cold resistance of a terminal pair determined in accordance with the rules in this standard, ohms,
T_o is the temperature (°C) corresponding to cold resistance, R_o,
T_r is the average winding temperature rise of a terminal pair, °C,
T_a is the ambient temperature corresponding to hot resistance, R,
R is the hot resistance of a terminal pair, ohms,
T_k is 234.5 °C for copper,
T_k is 225 °C for aluminum.

NOTE—Other values for T_k may be used if substantiated by test data. The value of T_k for aluminum may be as high as 240 °C for alloyed aluminum.

11.7 Correction factors

Correction factors shall be applied to the average winding temperature rise, T_r , as follows:

a) Ambient temperature other than 30 °C,
b) Test current other than rated current,
c) Altitudes above 1000 m.

11.7.1 Correction for ambient air temperature

When the ambient air temperature at the conclusion of the test is other than T_{ra} (usually 30 °C) the average winding temperature rise, T_r , shall be corrected by the following equation:

$$T_{c1} = T_r[(T_r + T_k + T_{ra})/(T_r + T_k + T_a)]^n \tag{23}$$

where

T_{c1} is the average winding temperature rise corrected for ambient temperature,
T_r is the measured average winding temperature rise,°C,
T_a is the ambient temperature at end of test,°C,
T_{ra} is the ambient temperature at rated kVA,°C, usually 30°C,
T_k is 234.5 °C for copper windings,
T_k is 225 °C for aluminum windings,

n is 0.80 for ventilated self cooled,
is 1.0 for ventilated forced air,
is 0.70 for sealed or nonventilated units.

NOTE—Other values for T_k may be used if substantiated by test data. The value of T_k may be as high as 240 °C for alloyed aluminum.

11.7.2 Correction for test current different from rated current

If the test current differs from the rated current, a correction of the winding rise is required. The corrected winding rise shall be calculated using the following equation:

$$T_{c2} = T_{c1}\left(\frac{I_r}{I_t}\right)^{2n} \tag{24}$$

where

T_{c1} is defined in 11.7.1,
T_{c2} is average winding temperature rise corrected for rated current,°C,
I_t is test current,
I_r is rated current,
n is 0.7 for sealed units, 0.8 for self cooled, and 1.0 for forced air tests.

This correction may be used provided the test current and frequency do not differ from rated by more than 10%.

11.7.3 Correction of average winding temperature rise for variation in altitude

When tests are made at an altitude not exceeding 1000 m above sea level, no altitude correction shall be applied to the average winding temperature rise.

When a transformer that is tested at an altitude of 1000 m or less is to be operated at an altitude in excess of 1000 m, it shall be assumed that the average winding temperature rise will be given by the following equation:

$$T_{c3} = T_{c2}\{1 + [(A - 1000)/1000]F\} \tag{25}$$

where

T_{c3} is average winding temperature rise at the higher altitude,
T_{c2} is defined in 11.7.2,
A is altitude in meters,
F is an empirical factor given in Table 2 below.

Table 2—Empirical factor for various types of cooling

Type of cooling	Empirical factor, *F*
For dry-type, self cooled (AA)	0.005
For dry-type with auxiliary—forced air cooling (AA/FA)	0.006[a]
For dry-type forced air cooled (AFA)	0.010

[a]Applies to forced cooled rating only.

11.8 Temperature rise test loading methods

Temperature rise test methods for different types of dry-type transformers are given in Table 3 in the order of preference.

Table 3—Temperature rise test loading methods

Test method	Ventilated		Sealed or non-ventilated
	AA	FA	
a) Actual loading	X	X	X
b) Loading back (opposition)	X	X	X
c) Separate excitation loss and rated current	X	X	
d) Impedance KVA	X	X	X
e) Rated current plus additive factor	X	X	
f) Compromise			X

11.8.1 Actual loading

The actual loading method is the most accurate of all methods, but its energy requirements are excessive for large transformers. Transformers of small output may be tested under actual load conditions by loading them on a rheostat, bank of lamps, water box, or by similar methods.

11.8.2 Loading back (opposition)

The loading back method is a basic method for testing dry-type transformers and may be used when more than one unit is available for test.

The loading back method (opposition) method requires a greater amount of testing facilities and auxiliary equipment, and also energy consumption. Because of these requirements, the loading back method becomes increasingly difficult to perform as the size of the transformer increases.

11.8.2.1 Temperature rise of single-phase transformer by the loading back method

Duplicate single-phase transformers may be tested in the loading back method by connecting both high-voltage windings in parallel and both low-voltage windings in parallel, and by applying rated excitation voltage at rated frequency to one set of parallel windings (see Figure 27).

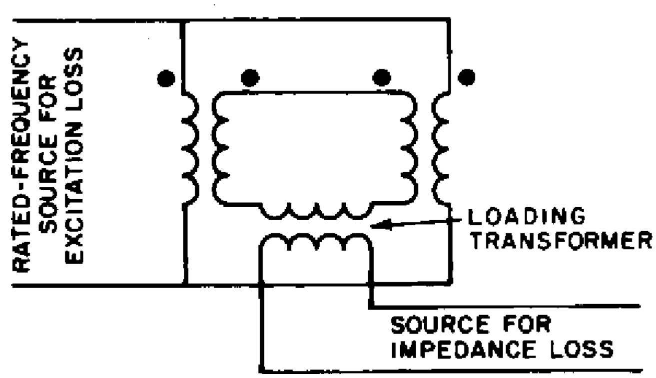


Figure 27—Two single-phase transformers in opposition

Circulate load current by opening the connections of either pair of windings at one point and impress a voltage across the break just sufficient enough to circulate rated current through the windings.

- This current should be at rated frequency (±10%).
- The correction to be applied when the circulating current is not at rated value is given in 11.7.2.

Run until equilibrium conditions are attained. Then shut down, measure the winding resistance, and calculate the average winding temperature rises above the ambient temperature, as described in 11.6 and 11.7.

11.8.2.2 Temperature rise test of three-phase transformers by the loading back method

Duplicate three-phase transformers may be tested by the loading back method by connecting both the high-voltage and low-voltage windings in parallel (see Figure 28).

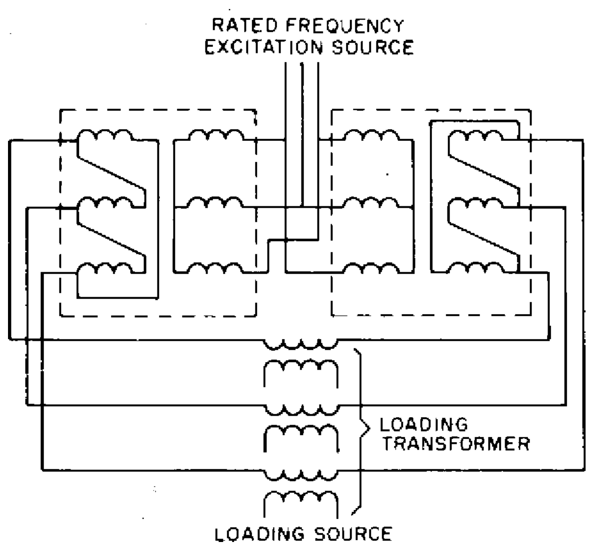


Figure 28—Two wye-delta-connected transformers

It is desirable to connect similarly marked leads together rather than attempt to connect windings in parallel by symmetry alone. Rated excitation voltage at rated frequency shall be applied to one set of windings. Circulate rated current by joining either set of windings through an auxiliary source of three-phase loading

voltage. The circulated current should be a rated frequency (±10%). The correction to be applied when the circulating current is not at rated value is given in 11.7.2.

The test should continue until equilibrium conditions are attained. The unit should then be shut down, the winding resistance measured, and the average winding rises over the ambient temperature calculated, as described in 11.6 and 11.7.

11.8.3 Separate excitation loss and rated current

When it is not feasible to make a loading back test, a separate excitation loss and rated current test may be performed.

This method has the advantage of permitting a direct measurement of the wattage and current being held during the temperature rise test. This method requires fewer testing facilities and a smaller amount of energy consumption. It is particularly suitable for the larger size transformers and is equally satisfactory for small transformers.

Temperature tests on individual ventilated dry-type units may be made utilizing the rises obtained in two separate tests—one with rated current alone and one with excitation loss alone, and calculating winding rises using the following formula:

$$T_t = T_c\left[1 + \left(\frac{T_e}{T_c}\right)^{1.25}\right]^{0.80} \tag{26}$$

where

- T_t is the total winding rise with full load current in the winding and normal excitation on the core. T_c shall be corrected if necessary; see 11.7.3.
- T_c is the high-voltage or low-voltage average winding temperature rise measured immediately following the rated current heat run with full-load current flowing in one winding and the other winding short-circuited. T_c shall be corrected if the test current is different than the rated current or the ambient temperature is different than 30 °C prior to the substitution in the above equation (see 11.7.1 and 11.7.2).
- T_e is the high-voltage or low-voltage winding rise measured immediately following the heat run with normal excitation on the core. T_e may be determined from units of similar ratings with the same core and excitation level.

11.8.4 Impedance method

A single three-phase transformer or a bank of three single-phase transformers may be tested, as shown in Figure 29, if both the high- and low-voltage windings can be connected in delta.

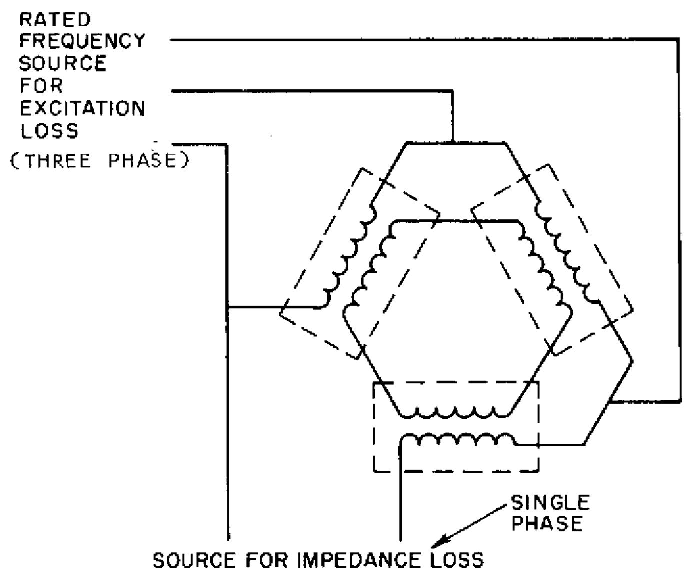


Figure 29—Delta-delta connections for one three-phase unit or three one-phase units

Rated three-phase voltage at rated frequency shall be applied to one of the deltas. A corner of either delta connection shall be opened, and a voltage from an auxiliary single-phase source shall be impressed across the break. This voltage shall be just sufficient enough to circulate rated current through the windings. The circulated current should be at rated frequency (±10%).

11.8.5 Rated current plus additive factor

The rated current test plus an additive factor may be used for all ventilated dry-type transformers when empirical data are available, establishing the proper value of the additive factor.

The total winding rise T_t of a single ventilated dry-type transformer may be calculated by applying an additive factor T_f to the rise T_c, as outlined in the next paragraph.

The additive factor T_f is an empirically determined temperature difference between the winding temperature rise obtained by loading back test (in accordance with 11.8.2.1 or 11.8.2.2) or separate excitation loss and rated current test (in accordance with 11.8.3) and the winding temperature rise measured with the rated current only. It shall be established by test data on units of similar construction.

The total winding rise T_t is given by

$$T_t = T_c + T_f \tag{27}$$

11.8.6 Compromise test method

When it is not feasible to make a loading back temperature test on a sealed or nonventilated dry-type transformer, a combination of tests involving an excitation temperature rise test, a current temperature rise test, and a total loss temperature rise test may be used to calculate the temperature rise of the windings.

With this test method it is necessary to measure the tank temperature. Thermocouple locations are shown in Figure 30.

a) Install three to five thermocouples on the tank wall at approximately equal vertical spacings. Install three thermocouples on the center line of the long dimension of the cover.
b) Conduct an excitation run until the external top surface and side surface temperature rises as the tank or enclosure stabilize. Terminate the test, measure the high-voltage and low-voltage average winding temperature rises using the procedure described in 11.6 and 11.7, and record the watts loss. Also measure and record the average temperature rise over ambient for the tank or enclosure surfaces.
c) Make a current temperature rise test by maintaining rated current in the windings until surface temperatures of the tank or enclosure are again constant. Terminate the current run and determine the average winding temperature rises as described in 11.6 and 11.7. Measure and record the average temperature rise over ambient for the tank or enclosure surfaces, and record the watts loss.
d) Circulate the necessary current in the transformer windings to generate a loss equal to the load loss plus the excitation loss, and maintain this load until the tank or enclosure surfaces are again constant in temperature rise. Adjust the current as necessary to hold constant losses. Measure and record temperature rises of the tank or enclosure. Winding rise measurements are not required for this total loss run.

The enclosure or tank surface temperature shall be determined by averaging the thermocouple readings based on the tank surface area as shown in Figure 30 and the following equations. The area of the tank braces, if present, shall be ignored.

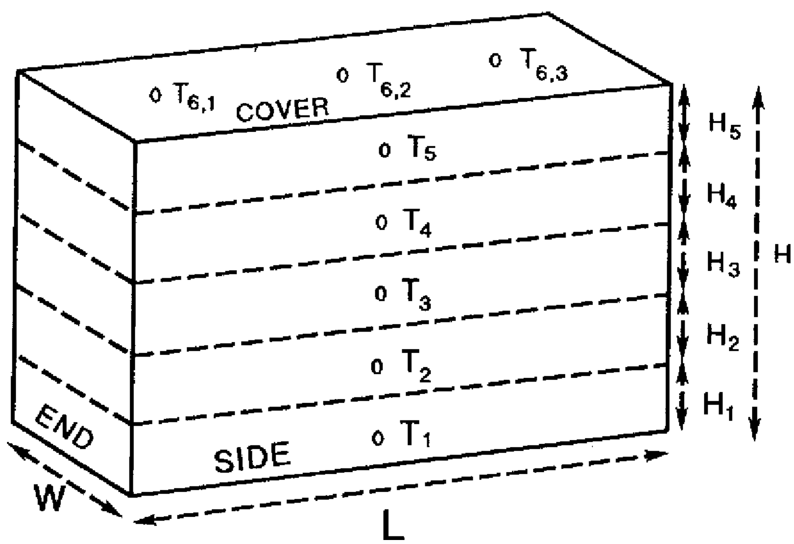


Figure 30—Thermocouple location and illustration of calculations for average tank or enclosure surface temperature

The enclosure average surface temperature shall be calculated as follows:

$$T_6 = (T_{6,1}T_{6,2}T_{6,3})/3 \quad (28)$$

$$A_1 = 2H_1(W+L) \quad (29)$$

$$A_2 = 2H_2(W+L) \quad (30)$$

$$A_3 = 2H_3(W+L) \quad (31)$$

$$A_4 = 2H_4(W+L) \quad (32)$$

$$A_5 = 2H_5(W + L) \tag{33}$$

$$A_6 = WL \tag{34}$$

$$T_s = \frac{\sum_{t=1}^{6} T_t A_t}{\sum_{t=1}^{6} A_t} \text{(average value)} \tag{35}$$

where

T_s is the enclosure surface average temperature, °C,
T_t is the temperature of a tank surface, °C,
A_t is the area of the tank surface at temperature, T_t, square inches,
t is the number of the horizontal band, 1 to 6 counting cover.

The high-voltage and low-voltage average winding temperature rises over ambient shall be determined by the following equations:

$$Tsre = Tse - Ta \tag{36}$$

$$Te = Twre - Tsre \tag{37}$$

$$Tsrc = Tsc - Ta \tag{38}$$

$$Tc = Twrc - Tsrc \tag{39}$$

$$Tsrt = Tst - Ta \tag{40}$$

$$Twr = Tsrt + Tc[1 + Te/(Tc^{1.25})]^{0.80} \tag{41}$$

where

Ta is ambient temperature, °C,
Tse is the average enclosure surface temperature during the excitation temperature rise test,
Tsre is the average enclosure surface temperature rise during the excitation temperature rise test,
Twre is the high-voltage or low-voltage average winding temperature rise over ambient during the excitation temperature rise test,
Te is the high-voltage or low-voltage average winding temperature rise over the enclosure surface temperature during the excitation temperature rise test,
Tsc is the average enclosure surface temperature during the current temperature rise test,
Tsrc is the average enclosure surface temperature rise during the current temperature rise test,
Twrc is the high-voltage or low-voltage average winding temperature rise over ambient temperature during the current temperature rise test,
Tc is the high-voltage or low-voltage average winding temperature rise over the enclosure surface temperature during the current temperature rise test,
Tst is the average enclosure surface temperature during the total loss temperature rise test,
Tsrt is the average enclosure surface temperature rise during the total loss temperature rise test,
Twr is the high-voltage or low-voltage average winding rise by resistance over ambient temperature.

12. Short-circuit tests

12.1 Scope

This test code applies to dry-type distribution and power transformers 1 kVA and above. Within the scope, the following three categories shall be recognized:

Category	Single-phase (kVA)	Three-phase (kVA)
I	1–500	15–500
II	501–1667	501–5000
III	1668–10 000	5001–30 000

All kVA ratings are the minimum nameplate kVA for the principal windings. For autotransformers, the category shall be determined by the equivalent two-winding kVA (as defined in IEEE Std C57.12.80-1978).

The code defines a procedure by which the mechanical capability of a transformer to withstand short-circuit stresses may be demonstrated. The prescribed tests are not designed to verify thermal performance. Conformance to short-circuit thermal requirements shall be by calculation in accordance with IEEE Std C57.12.01-1998.

The short-circuit test procedure described herein is for the purpose of establishing that the performance of the transformer under test meets specification requirements.

The procedures described herein are intended to apply to short-circuit testing of new transformers at the manufacturer's test facilities; however, where available test facility power is limited or other factors are involved, field testing may be acceptable where adequate facilities are available. It is imperative, for field tests of transformer design adequacy, that test conditions be negotiated by those responsible for the application and for the design of the transformer.

12.2 Short-circuit testing techniques

12.2.1 Fault application

12.2.1.1 Two-winding transformers and autotransformers without tertiary windings

The short circuit may be applied on the transformer primary or secondary terminals as dictated by the available voltage source, but the secondary fault is preferred since it most closely represents the system fault condition. The short circuit shall be applied by means of suitable low-resistance connectors.

In order of preference, the tests may be conducted by either of the following:

a) Closing a breaker at the faulted terminal to apply a short circuit to the previously energized transformer
b) Closing a breaker at the source terminal to apply energy to the previously short-circuited transformer

To obtain the test current and maintain the transformer terminal voltage during testing, the supply voltage may be higher than the rated voltage of the windings being supplied (or of the specified tap for transformers with tappings).

When short-circuiting follows the application of the supply voltage, the supply voltage should not exceed 1.10 times the rated voltage of the winding (or tapping), unless otherwise approved by those responsible for the design of the transformer. When the short-circuiting of the winding for transformers with single concentric windings precedes the application of the supply voltage (preset method), the transformer winding farthest from the core should usually be connected to the supply. This will avoid possible saturation of the core and the magnetizing inrush current superimposed on the short-circuit current during the first few cycles. For shell-type transformers, or core-type transformers with double concentric windings, the preset test method should be used based upon negotiation by those responsible for the application and for the design of the transformers.

12.2.1.2 Fault type

The type of fault to be applied will be dependent on the available energy source. Any of the following may be used (given in order of preference for three-phase transformers):

a) Three-phase source: Three-phase short-circuit
b) Three-phase source: Single phase-to-ground short circuit
c) Single-phase source: Simulated three-phase short circuit. (For wye-connected windings, apply source or fault between one line terminal and the other two connected together. For delta-connected windings, apply source or fault between two line terminals with no connection to the other line terminal. This must be repeated for each of the three phases).
d) Single-phase source: Single-phase short circuit on one phase at a time (applies to all single-phase transformers)

12.2.1.3 Multiwinding transformers including autotransformers

For transformers with more than two windings, or autotransformers with tertiary or regulating windings, the test conditions for fault application will be subject to negotiations between those responsible for the application and for the design of the transformers.

When the primary winding is connected to the supply, either one or both of the secondary windings or either one or both of the common or tertiary windings for autotransformers may be short-circuited for the test.

For autotransformers with tertiary windings, it may also be necessary to consider other fault conditions, such as single phase-to-ground or double phase-to-ground faults with either the common or series, or both, as the source(s) of supply.

The fault types and terminals to which they are to be applied must be determined individually for each particular transformer. The maximum fault current for each winding shall be determined from calculations for the fault types specified in Clause 7 of IEEE Std C57.12.01-1998, considering various fault types, fault locations, and applicable system data. During testing, each winding shall be subjected to its maximum calculated fault current on at least one test. In general, a given fault type and location will not produce the maximum fault current in more than one winding; so it will be necessary to make tests with several different connections in order to evaluate fully the capability of all windings.

In order of preference, the tests may be conducted by doing either of the following:

a) Close a breaker at the faulted terminal to apply a short circuit to the previously energized transformer
b) Close a breaker at the source terminal to apply energy to the previously short-circuited transformer

12.2.1.4 Tap connection for tests

When the transformer is provided with taps in any winding, at least one test satisfying the asymmetrical current requirement shall be made on the tap connection that calculations predict will produce the most severe mechanical stresses. Extremes of the tap range, all taps out or all taps in, normally produce the most severe stresses; so tests on these connections are recommended. Tests on other taps, or connections in the case of dual-voltage windings, may be made if required to ensure design adequacy.

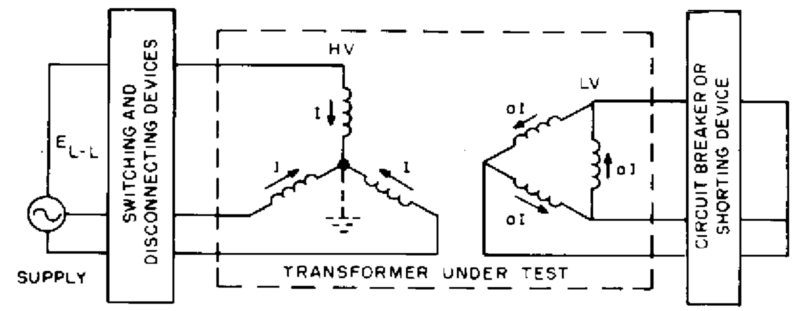
12.2.2 Test connections

12.2.2.1 Three-phase test

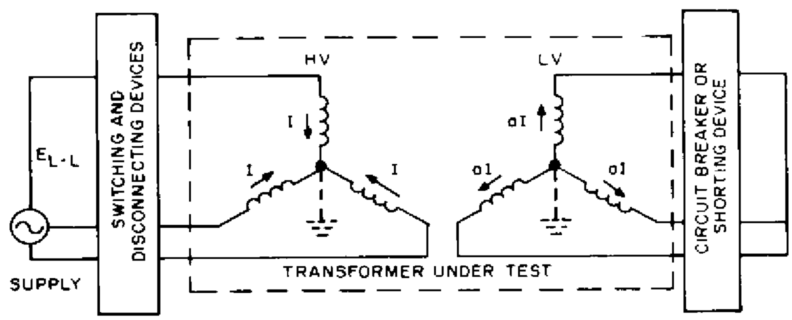
For three-phase two-winding transformers, a three-phase power supply is preferred. Depending upon the internal transformer connections, the preferred connections for testing are shown in Figure 31.

For three-phase multiwinding transformers, it may be required to perform both three-phase and single-phase short circuits to ensure that all significant winding conditions and connections have been investigated subject to negotiations between those responsible for the application and for the design of the transformer.

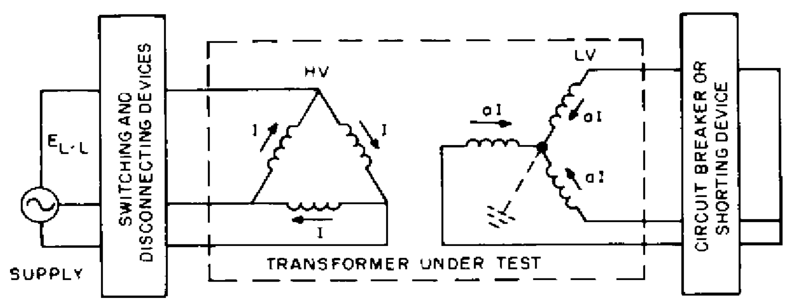
The transformer enclosure, the neutral of autotransformers, and the neutral of wye-connected transformers, when available and suitable, should be grounded. Current monitoring of the ground connection is recommended.



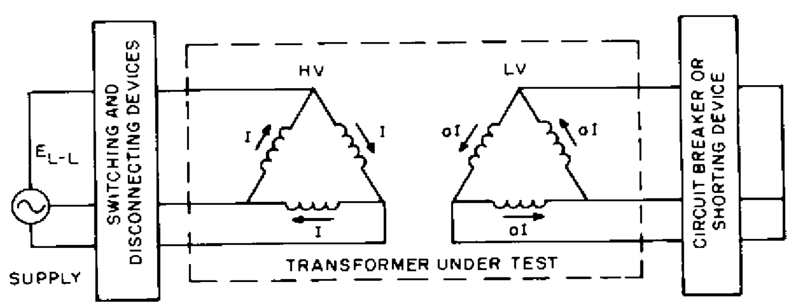
a) Wye-delta connection



b) Wye–wye connection

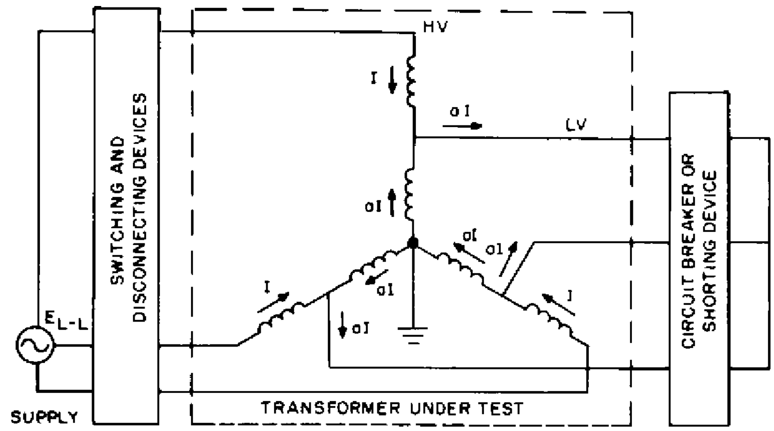


c) Delta-wye connection

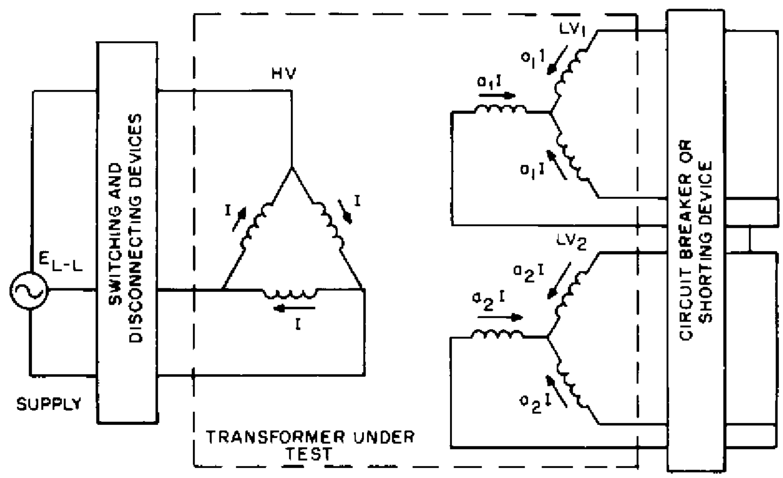


d) Delta-delta connection

Figure 31—Typical test connections for three-phase test



e) Autotransformer connection (two-winding)



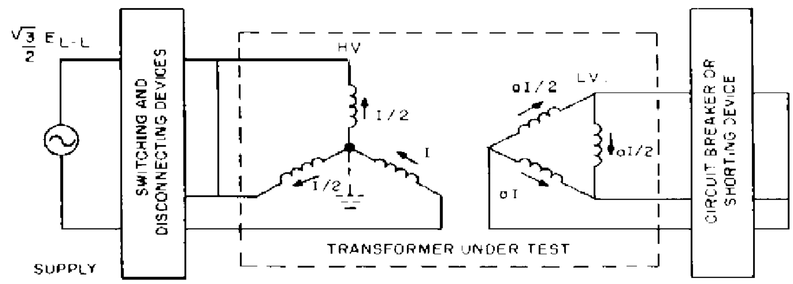
f) Delta-wye-wye connection

Figure 31—Typical test connections for three-phase test (continued)

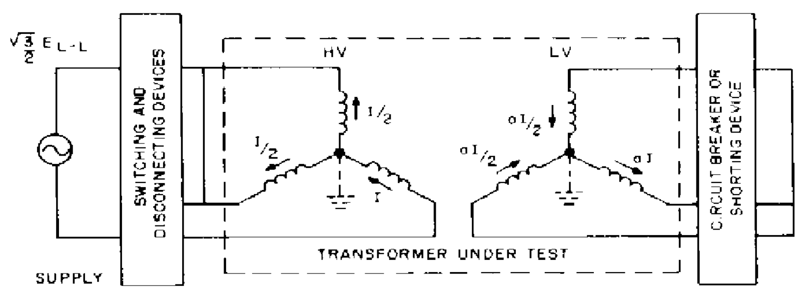
12.2.2.2 Single-phase test

12.2.2.2.1 Three-phase transformers

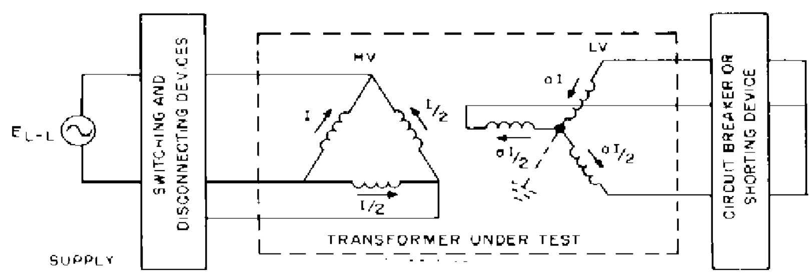
Three-phase transformers may be tested from a single-phase supply in those instances where a three-phase supply of sufficient capacity is not available. The three-phase fault connections can be simulated with a single-phase power supply. Test connections for the various internal winding connections and methods are given in Figure 32. The connections shown apply both to wye-connected windings with the neutral either available or not available.



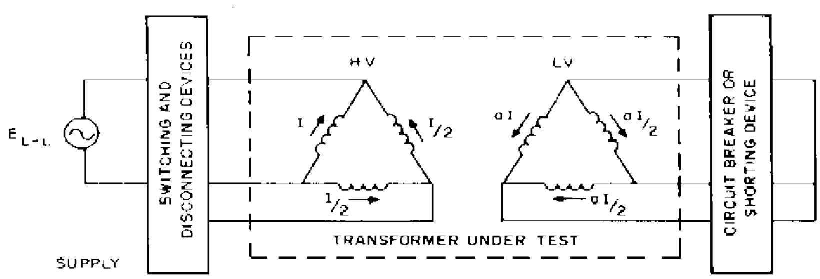
a) Wye-delta connection



b) Wye-wye connection



c) Delta-wye connection



d) Delta-delta connection

Figure 32—Typical simulated three-phase fault with single-phase supply

When the neutral point is not available, the insulation level of the neutral should be considered before proceeding with the short-circuit test.

For wye-connected windings where the neutral is available, single-phase tests between the line-end terminal and the neutral may be acceptable, subject to agreement between those responsible for the application and for the design of the transformer.

12.2.2.2.2 Single-phase transformers

Single-phase transformers should be tested with a single-phase supply voltage that should not exceed 1.10 times the rated voltage of the winding (or tapping) unless otherwise approved by those responsible for the design of the transformer.

12.3 Test requirements

12.3.1 Symmetrical current requirement—two-winding transformers

For two-winding transformers, the required value of symmetrical winding current for any test shall be determined from the equations in IEEE Std C57.12.01-1998.

NOTE—The symmetrical current magnitude shall not exceed the values listed in Clause 7 of IEEE Std C57.12.01-1998. For category I, calculate I_{sc} using transformer impedance only. For categories II and III, calculate I_{sc} using transformer plus system impedance. See 7.3.6.1 in IEEE Std C57.12.01-1998 for additional clarifying information on the determination of Z_s.

12.3.2 Symmetrical current requirement—multiwinding transformers and autotransformers

For multiwinding transformers and autotransformers, the required peak value of symmetrical current in each winding shall be determined by calculation based on applicable system conditions and fault types.

12.3.3 Asymmetrical current requirement

The required first-cycle peak for asymmetrical winding current tests shall be calculated in accordance with the equations in IEEE Std C57.12.01-1998.

12.3.4 Number of tests

Each phase of the transformer shall be subjected to a total of six tests satisfying the symmetrical current requirement specified in 12.3.1 and 12.3.2. Two of these tests on each phase shall also satisfy the asymmetrical current requirements specified in 12.3.3.

12.3.5 Duration of test

The duration of each short-circuit test should be in accordance with IEEE Std C57.12.01-1998.

12.3.6 Temperature limits

For dry-type transformers, the ambient air temperature at the start of the test shall be between 0 °C and 40 °C.

12.4 Test procedure

12.4.1 Condition of transformer to be tested

The transformer to be tested should have received the standard factory routine tests in accordance with IEEE Std C57.12.01-1998. In addition, impedance measurements on all taps shall be made. Prior to testing, a satisfactory internal condition of the transformer should be established. Internal inspections may be required.

12.4.2 Instrumentation

All oscillographic current and voltage inputs, conventional or special relaying and protection, and other special oscillographic inputs or event recorders should have a periodic calibration schedule. Evidence of adherence to the calibration schedule should be checked prior to transformer testing.

12.4.3 Synchronous timing

To produce the fully asymmetrical current wave specified in 12.3 at the time of transformer short-circuit initiation, the closing circuit breaker or device should be timed for calibration purposes prior to each test. In some cases, it may only be necessary to make this synchronous timing check prior to the first test. In most cases, control of the closing angle within ±15° from the zero point on the voltage wave will produce satisfactory results and maximum asymmetry.

12.4.4 Calibration tests and fault-current control

For factory testing, it is usual to make a calibration and timing test with approximately 50% of the supply voltage necessary to produce the required short-circuit current. For field tests, this calibration test at reduced supply voltage and fault current is made in most cases by transformer tap changing control of the supply voltage or system bus and line arrangements, or both, to reduce available short-circuit duty. A reduction of the required fault current is normally preferred for calibration purposes.

In addition to fault closing angle, initial fault current magnitude is a function of supply voltage, total circuit impedance, and circuit X/R ratio. Usual methods for fault-current control in factory or field testing include adjustment of one or more of the following test circuit parameters and equipment:

a) Supply voltage control with voltage regulators or transformer de-energized and energized tap changers
b) Available test circuit short-circuit capacity by generator, bus and line arrangements, and connections
c) Control of fault initiation with respect to supply voltage closing angle
d) Insertion of additional resistance to compensate total circuit reactance
e) Special choice of transformer fault connections or test circuit neutral grounding

Tests with voltage equal to or greater than that required to produce 95% of the specified symmetrical short-circuit current may be counted toward fulfillment of the required number of tests.

12.4.5 Voltage measurement

Oscillographic voltage measurements on the source side of the transformer under test are required for maximum information since the low-side voltage will be zero. The preferred method of measurement is to use potential transformers of suitable ratio coupled to oscillographic recording devices. Potential transformers should be connected line-to-line for three-phase tests on transformers with delta-connected primary windings and line-to-neutral for transformers with wye-connected primary windings where the neutral is accessible. When the neutral of the wye-connected winding is grounded or for single-phase tests with one line grounded, capacitance resistance dividers suitably coupled to oscillographic recording devices are satisfactory for these voltage measurements. In all cases, calibration of the oscillographic trace of the voltage should have an accuracy of ±5%.

When the short circuit is applied to a previously energized transformer, the voltage measurement should be made as close as possible to the primary terminals of the transformer being tested. When test power limitations require that power must be applied to the previously shorted transformer, the voltage measurement should be made on the source side of the primary circuit breaker.

12.4.6 Current measurements

For maximum data, oscillographic current measurements are required for each phase of the transformer being tested. The preferred method is to use CTs of suitable ratio coupled to oscillographic recording devices. When current measurements can be made on the grounded secondary side of the transformer and for single-phase tests with one line grounded, current shunts may be used to measure the phase currents. The connection from the CT secondary or shunt to the coupling and recording devices should be with shielded coaxial cable.

For direct information, the current measurements for establishing test current magnitude are normally made in the phase lines of the wye-connected winding for the transformer being tested. When this winding is connected to the energy source, phase currents are measured directly. When the wye-connected winding is the secondary winding, it is necessary to convert to the source winding by the inverse transformer turns ratio.

During short-circuit tests, it is recommended that the enclosure of the transformer under test be connected to ground through a current monitoring device. Either a CT or a current shunt coupled to an oscillographic device may be used. The current monitor should be sized to correspond to the short-circuit primary line amperes (see Figure 33).

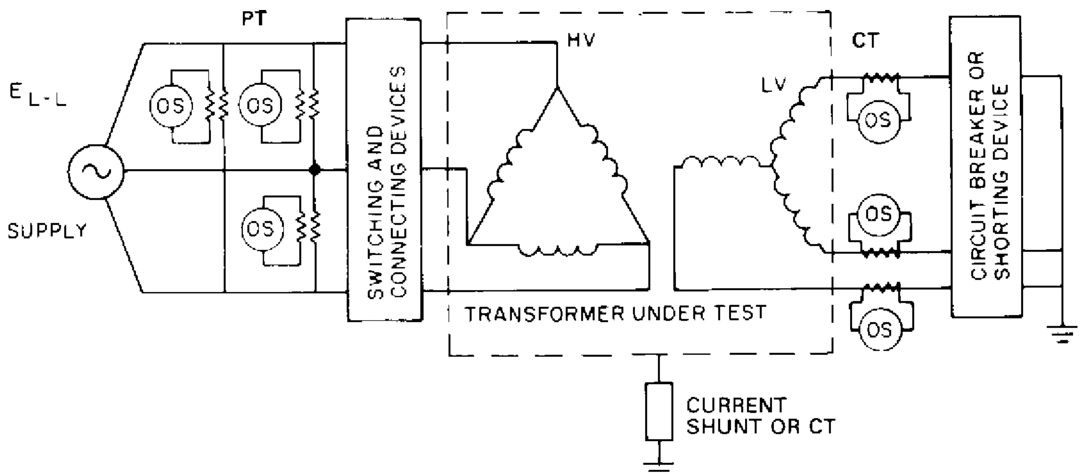


Figure 33—Typical connections of potential transformers, CTs, and current shunts to oscillographic recording devices

In all cases, whether the current measurement is made by use of CTs or current shunts, calibration of the oscillographic trace of the current should have an accuracy of ±5%. Current magnitudes shall be measured on the transformer terminals connected to the energy source. The symmetrical peak current shall be established as one-half of the peak-to-peak envelope of the current wave, measured at the midpoint of the second cycle of test current. If the transformer winding connected to the energy source is wye connected, the first-cycle peak asymmetrical current in each phase of the winding shall be measured directly from the oscillogram of terminal currents. If the transformer winding connected to the energy source is delta connected, the first-cycle peak asymmetrical current cannot be determined directly from terminal measurements at the source terminals. The following alternatives exist:

a) Measure first-cycle peak asymmetrical current on oscillograms at the faulted terminals, if the faulted winding is wye connected. Convert to source winding current by inverse turns ratio.
b) If all windings are delta connected, connect metering accuracy CTs having suitable current ratios inside the delta of the source winding and measure first-cycle peak asymmetrical current from oscillograms obtained from these CTs.
c) If all windings are delta connected, determine only symmetrical currents on the external lines and time-fault application for the instant that would produce peak asymmetrical current in the required phase winding. (Close breaker at a time close to voltage zero for the given phase winding, with appropriate timing adjustment to account for the R/X ratio of the test system plus transformer.)

12.4.7 Terminal voltage limits

If tests are to be made by applying the short circuit to the energized transformer, the no-load source voltage shall not exceed 110% of the rated tap voltage, unless otherwise approved by the manufacturer. Throughout the course of any test, the voltage at the transformer source terminals shall be maintained within a range of 95–105% of that necessary to produce the required symmetrical short-circuit current as determined in 12.3.1.

12.4.8 Tolerances on required currents

The measured currents, symmetrical or asymmetrical, in the tested phase or phases shall not be less than 95% of the required current. The required current shall take into account the measured impedance variation resulting from the test, if any, and any significant variation among the individual per-phase impedances inherent in the transformer design.

If test equipment parameters cause difficulty in achieving in a single test the prescribed value of the first-cycle asymmetrical peak current, without subjecting the transformer to a higher value of symmetrical short-circuit current than is required, the relationship of these current values may be adjusted by changing the angle at which the synchronous switch is closed to control the timing of the fault application to obtain the correct values within the tolerance limits.

12.4.9 Short-circuit test by shorting a previously energized transformer

This is the preferred condition and current measurements can be made as described in 12.4.6.

When both windings of the transformer are delta-connected, direct measurement of the phase currents cannot be made unless the transformer under test is provided with an internal CT of suitable ratio for the test. When no internal CTs are provided, the line currents are monitored in the usual manner. Dependence is made on the measured symmetrical current and the time of fault application for the instant that produces the maximum peak asymmetrical current in the required phase winding. Maximum peak asymmetry is obtained when the short circuit is initiated at the zero point on the voltage wave.

12.4.10 Short-circuit test by applying voltage to a previously short-circuited transformer

When the test is performed in this manner, portions of the transformer magnetic circuit will normally saturate. When saturation occurs, the excitation current required for the necessary flux may be greater than normal. This has the effect of lowering the impedance as seen from the excited side and a consequent increase in current in the excited winding. For this reason, it is recommended that all currents under this condition of test be monitored on the source side of the transformer being tested. For all transformers with delta-connected primary windings and no internal CTs, the symmetrical and asymmetrical currents should be determined as for the delta-delta connection.

To minimize or eliminate core saturation in core-type transformers, the following precautions can be taken:

a) Energize the outside winding and short-circuit the winding next to the core.
b) Bias the core with a remanent flux that simulates the normal operating flux condition in the core at the time of fault application.
c) A less desirable alternative is to demagnetize the core before each test.

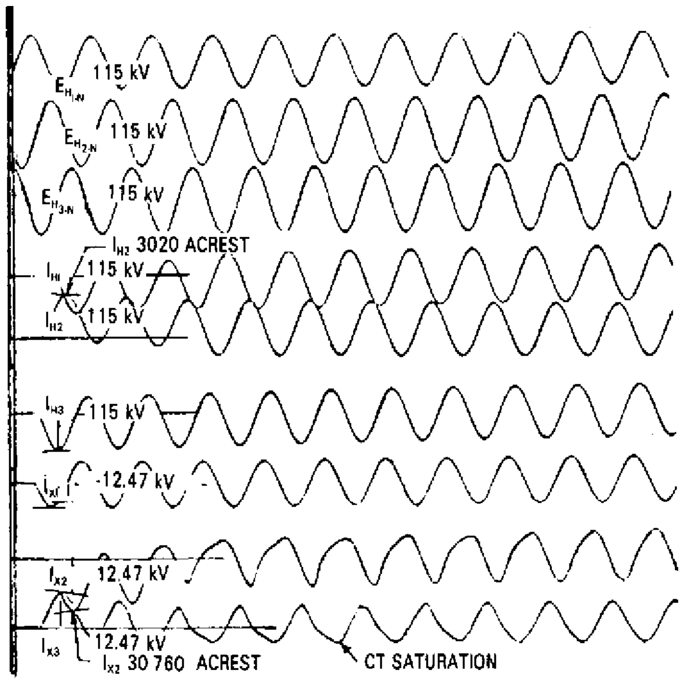
12.4.11 Temperature test

The transformer shall meet the specified average winding temperature rise by resistance values in accordance with IEEE Std C57.12.01-1998 .

12.5 Failure detection techniques

12.5.1 Voltage and current waveshapes

Abrupt changes in the waveshape of either current or voltage during the test indicate an internal electrical failure. Figure 34 shows a definite current magnitude and waveshape change two cycles after fault initiation, which resulted from shorted turns. It is, however, possible for shorted turns to develop without any detectable change in waveshape; the absence of changes should, therefore, not be considered, per se, as evidence of a successful test.



TEST TRANSFORMER NO 4 OSCILLOGRAPH RECORD OF TEST NO 2, FAULT CURRENT DISTORTION

Figure 34—Oscillograph record of fault current distortion

12.5.2 Leakage impedance

Acceptable repeatability is a function of the allowable variation specified by the test code. For the best results, digital instruments in a temperature-controlled environment can achieve repeatability within 0.1%. It is essential that the 60 Hz measuring source waveform be the same for each impedance test.

Inductive bridge measurements have been found acceptable in many cases.

When impedance changes occur, possible winding movement can be better evaluated by making measurements from both high and low sides. Increase of impedance measured from both directions is an indication of winding deformation on the leg.

It is important that the single-phase impedance measurements include only the windings on that leg. When the impedances of different legs are measured in parallel, separate winding impedance can only be determined by calculations.

12.5.3 Excitation current

Rated voltage excitation current tests are recommended, when practical. Low-voltage excitation current tests may be made, but remanent flux in the core may make the results undependable. Demagnetization may be necessary to produce acceptable results.

12.5.4 Dielectric tests

Following the short circuit test, the transformer shall withstand standard applied-voltage and induced-voltage tests at the full specification level in accordance with IEEE Std C57.12.01-1998. When impulse tests have been made prior to the short-circuit tests, the impulse tests shall be repeated if specified.

12.6 Analysis of test results and visual inspection

12.6.1 Terminal measurements

12.6.1.1 Current and voltage changes

Any increase or unusual variations greater than 5% in the current magnitude as determined from the current oscillogram, either during the asymmetrical or symmetrical period, is a potential indication of an internal electrical or mechanical failure.

External flashovers are usually visible and should be investigated before proceeding with further tests. Unusual changes in the magnitude or waveform as shown on the current oscillogram during the asymmetrical current flow may be an indication of core saturation of an improperly sized measuring CT.

Current magnitude increases insufficient to operate the circuit backup protective relays and not attributable to external circuit conditions indicate a partial-winding insulation breakdown, abnormal ground in the winding assembly, partial flashovers or internal discharges, etc. Additional routine electrical tests such as ratio, impedance, core loss, and insulation resistance may be necessary for detection of nondisruptive, partial, or intermittent failures.

An internal core and winding inspection will usually detect electrical failure locations or mechanical deficiencies. Transformer impedance changes, voltage regulation of the supply or system testing source, and conductor heating will, to some extent, cause magnitude reductions on the current oscillogram. In most cases, reduced current magnitudes, particularly following the decrement period for the fault current flow, establishes the voltage regulation of the supply circuit or the capability to maintain constant voltage during the fault period.

Major changes in the voltage oscillograms, such as voltage collapse, indicate an internal electrical failure if not attributable to external circuit conditions. Smaller voltage changes during the test are usually indicative of the voltage regulation of the supply or test circuit.

12.6.1.2 Leakage impedance changes

Leakage inductance should be measured between each pair of windings after each short-circuit test. This measurement normally is made at least 15 min following the short-circuit test. While consensus is that this is not a very sensitive test of short-circuit failure, increases in inductance are an indication of winding movements. Small increases after each successive test indicate progressive movement and may be a prediction of a failure.

For core-type transformers with concentric windings, small movements in an axial direction cause small increases in inductance, but movement in the axial direction can result in transformer failure because of its

progressive nature. In general, axial movements increase short-circuit forces, which further increase the movement finally resulting in winding collapse or failure of the end-supporting structure.

For core-type transformers with concentric windings, small movements in the radial direction, while causing an increase in inductance, may not be of serious consequence. This is particularly true of noncircular windings on a rectangular core form. In this case, the flat side of the outer winding tends to bulge outward and those of the inner winding tend to move inward toward the core. This radial movement may cause a large change in inductance which, in the general case, may not be critical to the service life of the transformer. For this reason, a larger impedance variation during short-circuit testing is permitted for this type of transformer construction. While changes in impedance are permitted under the test code, any change in impedance is acceptable only when the integrity of the insulation system is maintained. For this reason, it is recommended that an impulse test be included in the dielectric tests to be made on transformers with impedance changes approaching the limits of the test code.

12.6.1.3 Excitation current changes

Exciting current tests should be made at rated voltage, but can be made at reduced voltages when the core is demagnetized before each reduced voltage test. The purpose of this test is to detect short circuits between turns or layers of a winding. In the case of windings with multiple strands, it may detect shorts between different strands of different turns.

Any decrease in exciting current is not considered significant and is probably due to a reduction of mechanical strains in the core during the test. Any turn short or short between layers in power transformer windings will cause an increase in exciting current for that leg of the core much greater than the 5% permitted by the test code; however, distribution transformers with wound-type cores may experience increases up to 25% without impairing the function of the transformer due to smaller distortions of the core.

A short between different strands of different turns in a multiple strand winding may also increase the exciting current for that leg of the core more than 5% and a failure is again indicated. The increase in exciting current for this case is dependent on the location of the strand short with respect to the nearest (electrical circuit length) mass braze or connection of all strands in that winding. A strand short will result in a circulating current in the shorted strands determined by the volts per turn on the core and the circuit resistance between the strand short and the mass connections of the strands.

In combination with reductions in exciting current by relief of mechanical strains, some strand shorts may cause increases in exciting current that are not detected as obvious failures. In cases where a failure is suspected, a confirmation may by obtained by a comparison of core loss before and after the short-circuit test. These core loss tests should be made at rated voltage.

For three-phase units, this comparison is best made by comparing single-phase core losses on each core leg with proper allowance made for the differences in losses for each leg due to the dissymmetry of the magnetic circuit. Core loss for a core leg containing a strand short will usually increase by at least 25%.

12.6.2 Visual inspection

Visual inspection of the core and coils shall give no indication that there has been any change in mechanical condition that will impair the function of the transformer. The extent of the visual inspection shall be established on the basis of combined evidence obtained from the terminal measurements described in 12.6.1.1 through 12.6.1.3. If the terminal measurements give no indication of change in condition, external inspection of the core and coils removed from the enclosure or tank may suffice. Any evidence of change in condition from more than one of the terminal measurements would warrant disassembly of the windings from the core for a more detailed inspection. It is generally recommended that disassembly of a transformer be performed with factory facilities and supervision.

12.6.2.1 Inspection of assembled transformer

Frequently, sufficient evidence can be obtained from diagnostic electrical tests to limit the visual inspection of a tested transformer to the core coil only. In such cases, the following items discussed in 12.6.2.1.1 through 12.6.2.1.5 should be thoroughly inspected.

12.6.2.1.1 Cable leads and bus bars

Cable leads or bus bars, or both, should be inspected for mechanical movement or distortion and electrical damage. Special attention should be given to inspecting leads from tap sections and regulating windings as these leads are frequently difficult to secure. Damage to leads emanating from inner windings may warrant disassembly to facilitate a more detailed inspection. The securing devices for cables and bus bars, such as structures, insulators, and ties, should be inspected for mechanical damage.

12.6.2.1.2 Windings

Winding conductors should be inspected for mechanical deformation and electrical damage. Special attention should be given to conductors at the winding ends, crossovers, tapped sections, and that portion of the winding in and opposite the core window area. Normally, inspection of windings of a transformer that has not been disassembled will be limited to the outer phase windings.

12.6.2.1.3 Winding clamping system

The winding clamping should be inspected for looseness and relaxation in applied pressure. Where applicable, before and after torque values on clamping bolts should be compared. Inspect all metal structures for bending and deflection. Inspect the top and bottom insulating blocks and spacers for looseness. When possible, ensure that clamping pressure is exerted on the inner winding conductors and not on winding cylinders or vertical duct spacers.

12.6.2.1.4 Insulation systems

Inspect the vertical alignment of key spacers. Where visible, insulation collars and winding cylinders should be inspected for cracks and evidence of crushing. If either is found, further disassembly may be warranted to permit a more detailed inspection of inner insulating structures and windings.

12.6.2.1.5 Core

Inspect the core, where visible, for misaligned and temperature discolored laminations. The core ground strap should be inspected for evidence of overheating.

12.6.2.2 Inspection of disassembled transformers

When specified by those responsible for the application of the transformer, or when warranted by damage discovered during inspection of the unit, it will be necessary to disassemble the unit to permit a more detailed visual inspection of components. Recommended items for inspection after removal of the outer phase windings are as follows.

12.6.2.2.1 Cable leads

Inspect winding leads emanating from the inner windings for mechanical and electrical damage.

12.6.2.2.2 Windings

Inspect the inner winding conductors for mechanical deformation and electrical damage.

12.6.2.2.3 Insulation systems

Inspect the vertical alignment of key spacers. Where visible, insulating collars and winding cylinders should be inspected for damage. Inspect vertical duct spacers for uniform circumferential spacing and alignment. Rods or other materials used for radial support at the core legs should be inspected for damage.

12.7 Proof of satisfactory performance

The transformer under test shall be judged to have performed satisfactorily if the visual inspection (see 12.6.2), dielectric tests (see 12.5.4), temperature test (see 12.4.11), impedance change (see 12.7.2), and excitation current change (see 12.7.3) criteria have been met. Recommended terminal measurements that may be made during the course of the tests but are not required to be made unless specified, are listed in 12.6.1. If the terminal measurements are made and the requirements of 12.6.1 and 12.6.2 have been met following all tests, it is probable that the transformer has sustained no mechanical damage during the test series. A composite evaluation of the degree to which all criteria of 12.6.1 through 12.6.2 have been met may indicate the need for a greater or lesser degree of visual inspection to confirm satisfactory performance. The evidence may be sufficient to permit a judgment of satisfactory performance to be made without complete dielectric tests. A decision to waive all or parts of the visual inspection or dielectric test criteria must be based on discussions and negotiation by all parties involved in specification and performance of short-circuit tests.

12.7.1 Waveshape of terminal voltage and current

No abrupt changes shall occur in the terminal voltage or short-circuit current waveshapes during any test.

12.7.2 Impedance

Impedance measured on a per-phase basis after the test series shall not differ from that measured before the test series by more than the values specified below:

Category I: The allowable variation shall be a function of the transformer impedance (Z_t) as follows:

Z_t (per unit)	Percentage variation
0.0299 or less	22.5–500 (Z_t)
0.0300 or more	7.5

Categories II or III: 5% allowable for noncircular concentric coils; 2% allowable variation for circular coils.

The measuring equipment must have the demonstrated capability of giving reproducible readings within an accuracy of ±0.2%.

12.7.3 Excitation current

Excitation current measured after the test series shall not increase above that measured before the test series by more than 5% for stacked-type cores. For transformers with wound-core construction, the increase shall not exceed 25%. The measuring equipment must have demonstrated capability of giving reproducible readings with an accuracy of ±0.5%.

12.7.4 Other diagnostic measurements

Other diagnostic measurements may be made during the course of the tests to evaluate whether there have been any sudden or progressive changes in the mechanical condition of the transformer. Such results may be

useful to the understanding of the response to short-circuit forces, but they shall not form part of the proof criteria.

12.8 Required information for transformer short-circuit test reports

The information required for short-circuit test reports of transformers is as follows:

a) Date and location of short-circuit tests
b) Transformer description and ratings
c) Test circuit details and diagrams
d) Test fault type, connections, duration, and number
e) Test procedure details
f) Measurements prior to, during, and after short-circuit tests including oscillograms of the terminal voltages and currents.
g) Test results and evaluation:
   1) Electrical
   2) Inspection details
h) Report and results of final routine and dielectric tests

13. Audible sound-level measurements

13.1 General

The audible sound generated by a transformer is composed of discrete tones, the frequencies of which are even multiples of the transformer excitation frequency. The audible sound generated by auxiliary cooling equipment, such as fans, has a more broadly and evenly distributed frequency composition. The *A-weighted* measurement characteristic best relates how the human ear responds to the complex transformer-generated sound, and it shall be used to determine the average sound-level performance of the transformer.

For some purposes, a frequency distribution of a transformer's sound is desirable and, when specified, it shall be measured in frequency bands (either octave or one-third octave) or as discrete frequencies, as specified.

13.2 Instrumentation

13.2.1 Sound level measurements

Sound level measurements shall be made with instrumentation that meets the requirements of ANSI S1.4-1983 and ANSI S1.4a-1985 for type 2 meters.

13.2.2 Octave-band frequency measurements

Octave-band or one-third-octave-band frequency measurements, when specified, shall be made with instrumentation that meets the requirements of ANSI S1.4a-1985 for type 2 meters together with the requirements of ANSI S1.11-1986 for type E, class II performance, or their equal.

13.2.3 Discrete-frequency measurements

Discrete-frequency measurements shall be made when specified or when test conditions necessitate. For a discrete frequency application, see [B3][5]. Instrumentation is not presently standardized; however, typical analyzer bandwidth characteristics deemed suitable are one-tenth octave; 1%, 3%, or 10% of the selected frequency; or 3 Hz, 10 Hz, or 50 Hz.

13.2.4 Use of wind screens

A suitable wind screen may be used where the air velocity, due to winds, prevailing drafts, or microphone locations in the proximity of fans, cause the readings to be in error. Suitable corrections, if necessary, shall be applied to readings taken with wind screens in place to ensure that only wind noise effects are negated.

13.3 Test conditions

13.3.1 Sound pressure level

Measurements should be made in an environment having an ambient sound pressure level at least 5 dB below the combined sound pressure level of the transformer and the ambient sound pressure level. When the ambient sound pressure level is 5 dB or more below the combined level of transformer and ambient, the corrections shown in Table 4 shall be applied to the combined transformer and ambient sound pressure level to obtain the transformer sound pressure level. When the difference between the ambient and the transformer sound pressure level is less than 5 dB, and it is only desired to know the sound pressure that the transformer does not exceed, a correction of –1.6 dB may be used. For one-third octave or narrow band measurements, the 5 dB difference shall apply to each frequency band in which measurements are being made.

When ambient sound conditions do not comply with the above, suitable corrections may be feasible when the ambient sound conditions are steady and discrete frequency sound levels are measured. For this condition, the details and method for making the measurements and the ambient corrections shall be agreed upon by those responsible for the design and application of the transformer.

13.3.2 Location

The transformer shall be located so that no acoustically reflecting surface is within 3.0 m of the transformer, other than the floor or ground.

Table 4—Ambient sound corrections

Difference in dB between combined transformer and ambient sound pressure level and the ambient sound pressure level	Correction in dB to be added to the sound pressure level of the transformer and ambient level to obtain ambient corrected sound pressure level of the transformer
5	–1.6
6	–1.3
7	–1.0
8	–0.8
9	–0.6
10	–0.4
Over 10	–0.0

[5]The numbers in brackets correspond to those of the bibliography in Annex A.

13.3.3 Energize at rated voltage and frequency

The transformer shall be connected for and energized at rated voltage and frequency at no load, and tests shall be made for the various ratings (AA, AA/FA, AFA, etc.) with fans operating, if appropriate, for the rating being tested.

13.4 Microphone positions

13.4.1 Reference sound-producing surface

The reference sound-producing surface of a transformer is a vertical surface that follows the contour of a taut string stretched around the periphery of the transformer or integral enclosure. This contour is to include external cooling features, switch compartments, terminal compartments, etc., but excludes minor extensions such as valves, gages, thermometers, conduit terminal boxes, and projections at or above cover height.

In consideration of safety and consistency of measurement, the reference sound producing surface near unenclosed live parts of field-assembled items such as switches, switchgear, and terminal compartments shall be moved outward from the taut string contour such as to be consistent with safe worker clearances as determined by the manufacturer for the voltage class of the live parts termination involved.

13.4.2 Location points

The first microphone location point shall coincide with the nameplate. Additional points shall be located at 1.0 m intervals, proceeding clockwise in a horizontal direction, as viewed from above, along the reference sound-producing surface defined in 13.4.1.

There shall be no fewer than four microphone location points, which may result in intervals of less than 1.0 m for small transformers. The microphone shall be located on a straight line perpendicular to the reference sound-producing surface at each microphone location point. The microphone shall be spaced 0.30 m from the reference sound-producing surface, except that when fans are in operation, the microphone shall be spaced 2.0 m from any portion of the transformer external cooling feature cooled by forced air.

13.4.3 Measurement elevation

For transformers having an overall tank or enclosure height of less than 2.4 m, measurements shall be made at half-height. For transformers having an overall tank or enclosure height of 2.4 m or more, measurements shall be made at one-third and two-thirds height.

13.5 Sound level measurements

13.5.1 Test code conformance

Sound levels shall be measured in conformance with 13.2.1, 13.3, and 13.4 using the sound-level meter A-weighted characteristic.

13.5.2 Average A-weighted sound level

The average A-weighted sound level is defined as the arithmetic mean of the respective A-weighted sound-level measurements in dB(A) taken at each microphone location defined in this clause.

13.5.3 C-weighted measurements

When specified, measurements shall also be taken using the sound-level meter C-weighting characteristic.

13.5.4 Discrete-frequency components

If ambient conditions necessitate, the sound level may be measured using discrete-frequency components (see 13.6.1, [B3], and 13.6.4).

13.6 Optional-frequency analysis measurements

13.6.1 Frequency analysis

When specified, frequency analyses shall be made in accordance with 13.2, 13.3, and 13.4 from either octave, one-third octave, or discrete-frequency measurements. For a discrete-frequency application see [B3]. A-weighting, the C-weighting, or the flat response meter characteristic may be used. The weighting characteristic used shall be reported with the data.

13.6.2 Frequencies

Octave-band or one-third-octave-band frequency analysis measurements shall cover the interval of midband frequencies from 63 Hz through 4000 Hz, inclusive. Discrete-frequency-analysis measurements shall cover the fundamental through the seventh harmonic component (fundamental component is twice the excitation frequency).

13.6.3 Average level calculation

The average level for each frequency band measured shall be determined by taking the power average of the individual readings about the transformer; thus

$$L_x = 10\log 10\left(1/n\sum_{i=0}^{n}10^{\frac{L_i}{10}}\right), \text{dB} \tag{42}$$

where

L_x is average level for the X frequency band,
L_i is level in the X frequency band at the i^{th} measurement point,
n is total number of measuring points.

If the components are with A-weighting, the average is then with A-weighting.

13.6.4 Calculation of A-weighted sound level

If the average sound level, dB(A) as defined in 13.5.2, is to be determined from the individual A-weighted frequency band measurements at each microphone position, then an A-weighted sound level shall be calculated for each microphone position from the band measurements as follows:

$$L_A = 10\log 10\left(\sum_{j=1}^{n}10^{\frac{L_j}{10}}\right), \text{dB(A)} \tag{43}$$

where

L_A is calculated A-weighted sound level,
L_j is band level with A-weighting for the j^{th} band,
n is total number of bands.

Finally, the average sound level, dB(A), shall be determined as the arithmetic mean of the values of L_A for all microphone locations.

14. Mechanical design tests

Routine or design mechanical tests or analyses specified in IEEE Std C57.12.01-1998 shall be conducted as described in this clause.

14.1 Components involved in lifting or moving

14.1.1 Lifting or moving transformers

Design tests of components involved in the lifting or moving of transformers shall be conducted on typical components to verify that the designs conform to the safety standards in ANSI C57.12.50-1981, ANSI C57.12.51-1981, ANSI C57.12.52-1981, and ANSI C57.12.57-1987.

NOTE—Such tests are normally performed on components only (arranged to simulate normal application conditions) in mechanical testing machines rather than on complete transformers.

14.1.2 Lifting lugs

Tests of components such as lifting lugs shall be made with the test specimen arranged so that the angle of the lifting cable with respect to vertical will be the maximum angle allowed in applicable standards.

14.1.3 Pulling eyes or lugs

Tests of components such as pulling eyes or lugs for rolling or skidding shall be made in two directions:

a) In a direction parallel to the long axis of the transformer
b) In a direction perpendicular to the long axis of the transformer

14.1.4 Jacking facilities

Tests of jacking facilities shall be made under conditions simulating typical applications.

14.2 Tests of sealed dry-type transformers

14.2.1 Leak test

A leak test shall be performed as a routine test to verify the adequacy of sealing the transformer.

14.2.2 Tank pressure tests

Design tests shall be made at 125% of maximum operating pressure to demonstrate that sealed dry-type tank designs will withstand their maximum allowable pressure. This test pressure shall not produce permanent deformation.

15. Calculated data

15.1 Reference temperature

The reference temperature for determining total losses, voltage regulation, and efficiency shall be equal to the sum of the highest rated winding temperature rise plus 20 °C.

15.2 Total losses

Total losses are the sum of the no-load losses at room temperature (25 °C) and the load losses at reference temperature.

15.3 Efficiency

The efficiency of a transformer is the ratio of its useful power output to its total power input as follows:

$$\begin{aligned}\text{Efficiency} &= \frac{\text{output}}{\text{input}} = \frac{\text{input} - \text{losses}}{\text{input}} \\ &= 1 - \frac{\text{losses}}{\text{input}} \\ &= 1 - \frac{\text{losses}}{\text{losses} + \text{output}}\end{aligned} \tag{44}$$

When specified, efficiency shall be calculated on the basis of the reference temperature.

15.4 Voltage regulation

15.4.1 General

The voltage regulation of a transformer is defined in IEEE Std C57.12.80-1978. The regulation may be expressed in percentage (or per unit) on the basis of the rated secondary voltage at full load.

15.4.2 Impedance wattage and impedance voltage

The tests for impedance wattage and impedance voltage for use in the computation of voltage regulation may be measured at any convenient temperature and corrected using the correction factors applicable to the type of conductor material in the windings (see 5.3 and 9.4).

15.4.3 Voltage regulation computation two-winding transformers

When specified, the voltage regulation shall be computed as in 15.4.3.1.

15.4.3.1 Computation

Exact formulas for the calculation of regulation are

$$q = (1 - p^2)^{1/2} \tag{45}$$

$$r = \frac{\text{impedance loss (kW)}}{\text{rated (kVA)}} \tag{46}$$

$$x = (z^2 - r^2)^{1/2} \tag{47}$$

$$z = \frac{\text{impedance (kW)}}{\text{rated (kVA)}} \tag{48}$$

a) When the load is lagging

$$\text{reg} = [(r+p)^2 + (x+q)^2]^{1/2} - 1 \tag{49}$$

b) When the load is leading

$$\text{reg} = [(r+p)^2 + (x-q)^2]^{1/2} - 1 \tag{50}$$

where

p is the power factor of load,
q is the reactance factor of load,
r is the resistance factor of transformer,
x is the reactance factor of transformer,
z is the impedance factor.

The quantities p, q, x, z, and r are on a per-unit basis, so the result must be multiplied by 100 to get the regulation in percent.

15.4.3.2 Three-phase to two-phase transformers

For the calculation of the regulation for three-phase to two-phase transformation, proceed as follows:

a) For the per unit regulation of the main phase, use the impedance of the main transformer for substitution in the formula defined in 15.4.3.1.
b) For the per unit regulation of the teaser phase, use the sum of the impedance of the teaser transformer plus the interlacing impedance of the main transformer for substitution in the formula defined in 15.4.3.1.
c) To determine the interlacing impedance, connect the two ends of the three-phase winding of the main transformer together and impress between this common connection and the 50% tap, a voltage sufficient to pass three-phase line current in the supply lines.
d) The voltage thus determined is the interlacing impedance voltage and is to be put on a per unit basis by reference to the rated voltage of the teaser transformer on the 86.6% tap.

16. Minimum information to be included in certified test data

The test report shall include the following minimum information if certified test data is required.

16.1 Order data

a) Purchaser
b) Purchaser's order number
c) Manufacturer's serial number
d) Date of test

16.2 Rating data

a) Cooling class
b) Number of phases
c) Frequency
d) Insulation medium
e) Average winding temperature rise
f) Hottest spot temperature rise
g) Polarity
h) Winding ratings (kVA, V, insulation temperature class)

16.3 Test data

The results of all *routine* tests as defined in IEEE Std C57.12.01-1998 shall be included for each individual unit (by individual serial number). In addition, the results of all other tests as required by the customer order, either *design* or *other*, shall also be included, for each individual unit.

The most common data required is listed in the following:

a) Winding resistances
b) Losses: no-load, load, total
c) Impedance
d) Average temperature rise (when test is performed)
e) Hottest spot temperature rise (unless determined by calculation)
f) Applied-voltage test data
g) Induced-voltage test data
h) Impulse test data (when test is performed)
i) Sound level (when test is performed)

NOTE—All reported data should be corrected to reference temperature in accordance with 15.1.

16.4 Calculated data

a) Efficiency
b) Regulation (if specified)
c) Hottest spot temperature rise (unless determined by test)

16.5 Certification statement and approval

Annex A

(informative)

Bibliography

[B1] IEEE 100, *The Authoritative Dictionary of IEEE Standards Terms,* Seventh Edition.

[B2] Lech, W., and Tyminski, I. "New Method of Fault Indication in Dynamic Strength Testing Transformers," *Electrichestvo*, no. 1, pp. 77–81, 1966.

[B3] "Measurement of Self-Cooled Transformer Sound Levels in Relatively High Ambients," *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-89, pp. 1657–1662, Sept./Oct. 1970.

[B4] Waters, M., Stalewski, A., Farr, J. C., and Whitaker, J. D. "Short-Circuit Testing of Power Transformers and the Detection and Location Damage," *Conference Internationale des Grandes Reseaux Electriques a Hauté Tension*, Paper no. 12-05, 1968.